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On maintenance models under policies of restart and resume

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Abstract

In the course of processing a job, task or mission, various events can interrupt or disrupt the process. This is especially true in maintenance, where activities such as inspections, diagnoses, repairs and replacements can be interrupted by various events. In this paper, we consider two basic models, called the restart and resume models, to describe how the interrupted job can be continued or restarted. The definitions of both models are presented and the failure rate processes, point-wise and interval availabilities, breakdown counting processes, and virtual age processes are derived under the two models. Then, 10 derivative models are developed, which can closely fit real-world phenomena. Their relationship is also briefly considered. All these findings can enrich maintenance models and can help practitioners use them to fit different scenarios. We believe that this work can shed light on maintenance models, including the use of machine learning and AI for maintenance.

Keywords: restart model, resume model, virtual mission time, maintenance, policy

1. Introduction

Maintenance activities such as inspections, diagnoses, repairs and replacements can be classified into several categories. If we treat all these activities as jobs, then the jobs can be classified in terms of their sequential order into pre-emptive and non-pre-emptive ones, and/or precedence or non-precedence ones. A job or action that has pre-emptive priority over other jobs/actions, is called a pre-emptive one. For non-pre-emptive priority, this means that all jobs/actions in the working scope can be taken in an equal or random way. For example, the replacement of a failed component by a spare has a pre-emptive priority over the repair of the failed component. Without pre-emptive priority, then the replacement and repair actions can be chosen arbitrarily. For any kind of job or mission, regardless of the class the jobs belong to, it is natural that a maintenance activity or a job/mission can be interrupted or disrupted by any event, whether intentionally or unintentionally. In this situation, both in theory and practice, we need to treat the relationship between the interrupted job and its continuation, for which there are many ways to handle this relationship. Among these methods, the restart and resume policies or models are basic and fundamental, and they have been widely used in both theory and practice, including in maintenance, decision making, scheduuling, and other areas. In the present paper, we focus on the restart and resume policies and models in maintenance.

In maintenance, there are two basic and fundamental models to depict the subsequent job of an interrupted or disrupted action. They are called a restart (repeat) model and the resume model, respectively. *The restart model* describes a situation where, when processing begins again after an interrupted job, it restarts from the beginning of the job. That is, the total processing time of the job is the sum of all times spent on this job before and after interruptions, as if the last processing is only valid to finish the job. *The resume model* describes a situation where, processing begins again on the interrupted job, it resumes where it left off. That is, the total processing time of

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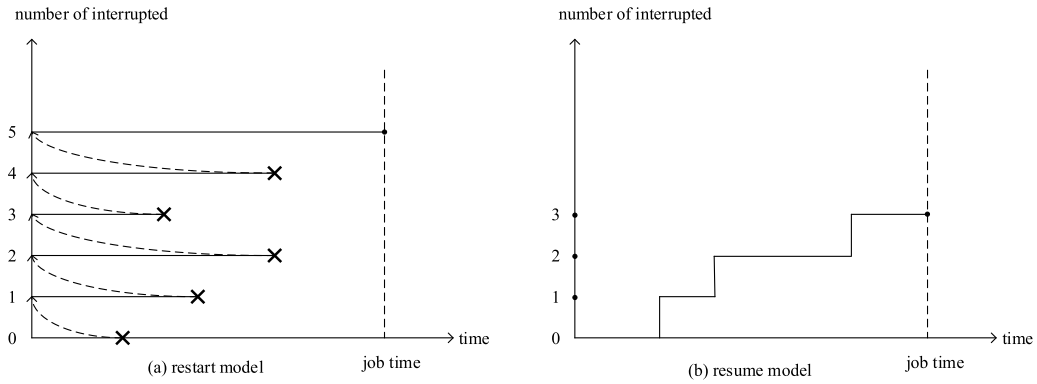


Figure 1. Implications of the two models.

the job is the same as if it had not been interrupted. Figure 1 shows both models

The two mentioned basic models can be thought of as the results of two corresponding working policies, especially in maintenance. These two maintenance policies, the restart policy and the resume policy, are fundamental policies in maintenance activities such as repairs, replacements, diagnoses and inspections.

There is much literature on restart and resume policies and models, although they are not often considered separately. It is difficult to determine which article first proposed the restart and resume policies and models. However, Kijima (1989) proposed Kijima models I and II, which include the restart and resume models as special cases. Cui (2008) also reviewed maintenance models in which both models are included. In general, there are several ways to describe the relationship between an interrupted job and its renewal job. They mainly are as follows: specified policy, virtual mission duration, connected information or transform information. The specified policy is often used, which determines where the job continues after an interruption. The virtual mission duration has become popular recently; for example, see Chen *et al* (2010), Qiu and Cui (2019), Finkelstein and Cha (2021), Cui (2021) and Cui *et al* (2025a). The connected information or transform information, in fact, a necessary step in multi-stage related models, as it specifies the relationship between mission durations at the end and beginning of adjacent stages. The restart and resume models have appeared in many related reviews or research papers; for example, in Alaswad and Xiang (2017), Zhu *et al* (2024), Ulansky and Raza (2025). Specifically, Birge *et al* (1990) called the restart model a repeat model in scheduling and Righter (1994) presented a survey of research on the pre-empt-resume model. Both models can be used in many subjects, including in maintenance and AI for reliability. For example, perfect (maximal) and minimal repairs can be thought of as coming from the resume and restart models, respectively. Some related recent review work on maintenance models include Pham (2024) and Arts *et al* (2025). Based on the mentioned literature, we have not found any review or survey work covering both models that include related characteristic measures of the two models. Thus we shall try to fill this gap in the context of maintenance.

The contribution of this paper is four-fold: (i) the restart and resume models, two fundamental maintenance models, are briefly summarized; (ii) four characteristic measures, namely failure rate processes, point-wise and interval availabilities, breakdown counting processes, and virtual age processes, are derived under two models; (iii) 10 derivative related models are introduced and their definitions are presented; and (iv) the relationships between the two basic models and 10 models are discussed.

Because the policies determine the models or subsequent job completion times (makespans), we shall use ‘model’ and ‘policy’ interchangeably, although they have different implications. The ‘mission time’ and ‘duration of job’ are used interchangeably throughout the paper.

2. Two class maintenance models and related assumptions

During job processing or mission execution, interruptions by unexpected events often occur. After this interruption, the job processing or mission execution must be continued, which naturally raises questions of how to deal with the finished part of job and how to handle the effects of the finished part of job on the subsequent job. The fundamental policies or models to answer this question are the ‘restart policy’ and ‘resume policy’ or the ‘restart model’ and ‘resume model’. In this section, the two basic policies and models are discussed in detail. It is obvious that the two policies can not only be used individually in job processing or mission execution, but also be employed in combination.

(1) Restart model

As mentioned in the previous section, the *restart model* or *repeat model* can depict the behavior of the interrupted job to be renewed again. This model results from the restart /repeat policy that follows a rule or a regulation: the interrupted job must be restarted again from the beginning of job as if the past work or effort is useless. This policy only specifies the rule at the moment the job is interrupted, rather than for the whole job process. Thus the restart model, in general, is only applied to a single interruption. For multiple interruptions

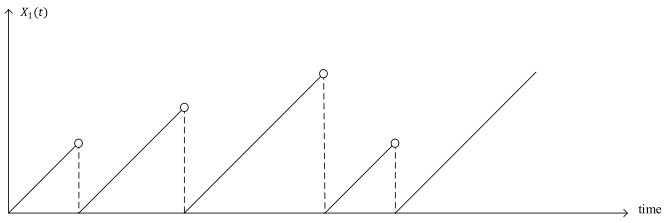


Figure 2. A possible path of $X_1(t)$.

of a job, one can follow or specify other rules or regulations for them. It is obvious that the restart model is fundamental for describing an interrupted job. There are many real-world examples that can be fitted by the restart model. For example, in maintenance, maximal repair and replacement activities can be modeled very well by the model. Further examples can be found in Chang (2014), Scarf *et al* (2024) and Park and Sung (2025). If it is assumed that all interrupted jobs follow the restart policy, then the elapsed job processing time before its completion can be expressed by

$$X_1(t) = t - t_{N_1(t)}, \tag{2.1}$$

where $X_1(t)$ is the elapsed job processing time at clock time t under the restart model, $N_1(t)$ is the number of interruption events of the job before clock time t, and $0 < t_1 < t_2 < \cdots < t_{N_1(t)}$ are the successive interrupted instants.

A possible path of $X_1(t)$ is shown in figure 2.

Let the lifetime of job processing be X, and $F(t)$,$f(t)$ and $\lambda(t)$ be the distribution function, probability density function and failure rate function of X, respectively. It is assumed that all job processing lifetimes are independent of one another, then the failure rate process can be given by

$$\begin{aligned}
&\lambda_{\text{restart}}(t)\\
&= \lambda(t)\,\mathbb{P}\{N_1(t)=0\} + \sum_{j=1}^{\infty}\int_0^t \lambda(t-u)\,[1-F(t-u)]f^{(j)}(u)\,\mathrm{d}u\\
&= \lambda(t)\,[1-F(t)] + \int_0^t \lambda(t-u)\,[1-F(t-u)]\sum_{j=1}^{\infty} f^{(j)}(u)\,\mathrm{d}u\\
&= f(t) + \int_0^t f(t-u)m(u)\,\mathrm{d}u,
\end{aligned} \tag{2.2}$$

where $m(t)=\sum_{j=1}^{\infty} f^{(j)}(t) = \frac{\mathrm{d}}{\mathrm{d}t}\mathbb{E}[N_1(t)]$, which is a renewal density function, and $f^{(j)}(t)$ is the j-fold convolution of $f(t)$ with itself. In fact, we can also consider the $\lambda_{\text{restart}}(t)$ in the following way:

$$\begin{aligned}
\lambda_{\text{restart}}(t) &= \lambda(t)\,\mathbb{P}\{N_1(t)=0\} + \int_0^t \lambda_{\text{restart}}(t-u)f(u)\,\mathrm{d}u\\
&= f(t) + \int_0^t f(t-u)\lambda_{\text{restart}}(u)\,\mathrm{d}u.
\end{aligned} \tag{2.3}$$

This is because the first renewal event occurs at time u and the remaining intensity function, having the same distribution as the original intensity function, is $\lambda_{\text{restart}}(t-u)$. In fact, based on the renewal equation,

$$\mathbb{E}[N_1(t)] = F(t) + \int_0^t \mathbb{E}[N_1(t-u)]f(u)\,\mathrm{d}u, \tag{2.4}$$

we have

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbb{E}[N_1(t)] = f(t) + \int_0^t \frac{\mathrm{d}}{\mathrm{d}t}\mathbb{E}[N_1(t-u)]f(u)\,\mathrm{d}u. \tag{2.5}$$

Furthermore, in terms of $\frac{\mathrm{d}}{\mathrm{d}t}\mathbb{E}[N_1(t)] = \mathbb{E}[\lambda_{\text{restart}}(t)]$ (see Cui *et al* (2020)), we have

$$\begin{aligned}
\lambda_{\text{restart}}(t) &= f(t) + \int_0^t \lambda_{\text{restart}}(t-u)f(u)\,\mathrm{d}u\\
&= f(t) + \int_0^t f(t-u)\,\lambda_{\text{restart}}(u)\,\mathrm{d}u.
\end{aligned} \tag{2.6}$$

Based on equations (2.2) or (2.3), it is easy to get

$$\lambda^*_{\text{restart}}(s) = \frac{f^*(s)}{1-f^*(s)}, \tag{2.7}$$

which is the Laplace transform of $\lambda_{\text{restart}}(t)$. (Note, the Laplace transform is defined by $\lambda^*_{\text{restart}}(s) = \int_0^{\infty} \mathrm{e}^{-st}\lambda_{\text{restart}}(t)\mathrm{d}t$.)

On the other hand, as mentioned above, all the breakdowns form a renewal process, denoted as $\{N_1(t), t \geqslant 0\}$, the corresponding renewal function, $m_1(t) = \mathbb{E}[N_1(t)]$, possess all related properties of the renewal process.

It is well known that the point-wise and interval availabilities under the restart model, when every repair time has the same distribution $G(t)$ (its pdf is denoted as $g(t)$), are located between two adjacent job processing times, as shown in figure 3. We have (see Cui *et al* 2025b),

$$A_{\text{restart}}(t) = [1-F(t)] + \int_0^t A_{\text{restart}}(t-u)\,[f*g(u)]\,\mathrm{d}u, \tag{2.8}$$

$$A^*_{\text{restart}}(s) = \frac{1-f^*(s)}{s\,[1-f^*(s)\,g^*(s)]}, \tag{2.9}$$

$$\begin{aligned}
A_{\text{restart}}([t,t+\Delta_0]) = [1-F(t+\Delta_0)] + \int_0^t A_{\text{restart}}([t-u,t-u+\Delta_0])\\
\times [f*g(u)]\,\mathrm{d}u,
\end{aligned} \tag{2.10}$$

$$A^*_{\text{restart}}([t,t+\Delta_0])(s) = \frac{1-F(\Delta_0)-f^*_{\Delta_0}(s)}{s\,[1-f^*(s)\,g^*(s)]}, \tag{2.11}$$

where $A_{\text{restart}}(t)$ and $A_{\text{restart}}([t,t+\Delta_0])$ are point-wise and interval availabilities, Δ_0 is a given interval length,

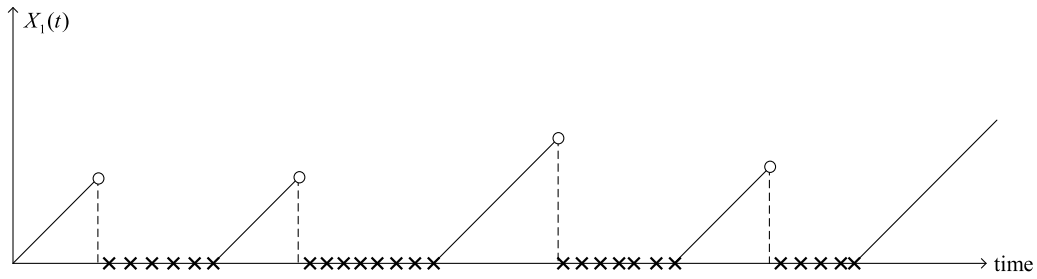


Figure 3. The process of breakdowns and repairs under the restart model.

$f*g(t)=\int_0^t f(t-u)g(u)\mathrm{d}u$, which is a convolution of functions $f(t)$ and $g(t)$, and $f^*_{\Delta_0}(s)=\int_0^\infty f(t+\Delta_0)\mathrm{e}^{-st}\mathrm{d}t$.

For the virtual age process $V_1(t)=X_1(t)=t-t_{N_1(t)}$ under the restart model, we have

$$\begin{aligned}\mathbb{E}\left[V_1(t)\right]&=t-\mathbb{E}\left[t_{N_1(t)}\right]=t-\mathbb{E}\left[N_1(t)\right]\mathbb{E}\left[X\right]\\&=t-\mathbb{E}\left[N_1(t)\right]\int_0^\infty\left[1-F(u)\right]\mathrm{d}u,\end{aligned}\tag{2.12}$$

where the renewal function $N_1(t)$ satisfies equation (2.4). The second and third equalities in equation (2.12) result from Wald's equation and the well-known result $\mathbb{E}[X]=\int_0^\infty[1-F(u)]\mathrm{d}u$.

(2) Resume model

The *resume model* can depict the behavior of an interrupted job continuing as if the interruption did not occur. This model results from a resume policy that follows a rule or a regulation: the interrupted job must be resumed from where it left off, which implies that all elapsed job processing times are useful and count towards the job's completion time. Similarly, this policy is also for a single interruption, but for multiple interruptions of a job, one can also follow or specify other rules or regulations for them. The resume model is also a basic one for depicting an interrupted job. Similarly, many real-world examples can be modeled by the resume model. For example, in maintenance, minimal repairs, imperfect repair activities, etc. Further examples can be seen in Asadi (2023), Tsai and Chien (2024) and Tekin *et al* (2025). If it is assumed that all interrupted jobs follow the resume policy, then the elapsed job processing time and interrupted interval durations before its completion can be expressed, respectively, by

$$X_2(t)=t,\text{and}$$
$$\Delta_i=t_i-t_{i-1},\left(0=t_0<t_1<\cdots<t_{N_2(t)}\right),$$

where $X_2(t)$ is the elapsed job processing time at clock time t under the resume model,

Δ_i $(i=1,2,\ldots,N_2(t))$ is for the ith interrupted interval.

A possible path of $X_2(t)$ is shown in figure 4.

From the above, we can know that both policies consider two extreme cases. That is, the restart policy specifies that all efforts must be totally discarded once an interruption event occurs, and the remainder of the job must be restarted from the beginning of the job. In contrast, the resume policy specifies that all efforts must be used even if interruption events occur.

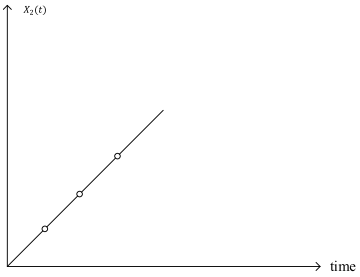


Figure 4. A possible path of $X_2(t)$.

Similarly, we show that the failure rate process can be given by

$$\begin{aligned}\lambda_{\text{resume}}(t)&=\lambda(t)\,\mathbb{P}\{N_2(t)=0\}\\&\quad+\sum_{j=1}^{\infty}\int_0^t\lambda(t)\left[1-F(u)\right]\cdot\frac{\left[\Lambda(u)\right]^{j-1}}{(j-1)!}\lambda(u)\,\mathrm{e}^{-\Lambda(u)}\mathrm{d}u\\&=\lambda(t)\left[1-F(t)\right]+\lambda(t)\int_0^t\left[1-F(u)\right]\\&\quad\cdot\lambda(u)\,\mathrm{e}^{-\Lambda(u)}\sum_{j=1}^{\infty}\frac{\left[\Lambda(u)\right]^{j-1}}{(j-1)!}\mathrm{d}u\\&=\lambda(t)\left[1-F(t)\right]+\lambda(t)\int_0^t f(u)\,\mathrm{d}u=\lambda(t),\end{aligned}\tag{2.13}$$

where $\{N_2(t),t\geqslant 0\}$ is the breakdown counting process for the system under the resume model and $\Lambda(t)=\int_0^t\lambda(u)\mathrm{d}u$.

Equation (2.13) for $\lambda_{\text{resume}}(t)$ results from (i) $\{N_2(t),t\geqslant 0\}$ being an inhomogeneous Poisson process with intensity function $\lambda(t)$ and (ii) the jth $(1\leqslant j)$ event arrival instant of $\{N_2(t),t\geqslant 0\}$ follows a distribution with pdf $\lambda(t)\frac{[\Lambda(t)]^{j-1}}{(j-1)!}\mathrm{e}^{-\Lambda(t)}$. In fact, $\lambda_{\text{resume}}(t)=\lambda(t)$, which is coincident with our intuition, because the breakdowns can be thought of as effect-free events under the resume model.

On the other hand, similarly, all the breakdowns form an inhomogeneous Poisson process denoted as $\{N_2(t),t\geqslant 0\}$,

that is,

$$\mathbb{P}\{N_2(t)-N_2(s)=k\}=\frac{[\Lambda(t,s)]^k}{k!}\mathrm{e}^{\{-\Lambda(t,s)\}},\quad k=0,1,\ldots,\quad 0\leqslant s<t, \tag{2.14}$$

where $\Lambda(t,s)=\int_s^t\lambda(u)\mathrm{d}u$. The process $\{N_2(t),t\geqslant 0\}$ satisfies all related properties of an inhomogeneous Poisson process.

In fact, based on the property of an inhomogeneous Poisson process, we have

$$\mathbb{E}[N_2(t)]=\sum_{i=1}^{\infty}i\mathbb{P}\{N_2(t)=i\}=\Lambda(t). \tag{2.15}$$

Furthermore, it also has

$$\mathbb{E}[\lambda_{\text{resume}}(t)]=\frac{\mathrm{d}}{\mathrm{d}t}\mathbb{E}[N_2(t)]=\lambda(t)=\lambda_{\text{resume}}(t). \tag{2.16}$$

Similarly, if the repair times have the same distribution $G(t)$ (its pdf is denoted as $g(t)$) and are located between two adjacent job processing times. Let $\{X_i\}_{i=1,2,\ldots}$ and $\{Y_i\}_{i=1,2,\ldots}$ be the job processing times and repair times sequentially, as shown in figure 5, then we have

$$\begin{aligned}A_{\text{resume}}(t)&=\mathbb{P}\{t<Y_1\}+\sum_{i=1}^{\infty}\mathbb{P}\left\{\sum_{k=1}^{i}(X_k+Y_k)\leqslant t<\sum_{k=1}^{i}(X_k+Y_k)+Y_{i+1}\right\}\\&=\mathbb{P}\{X_1<t\}+\sum_{i=1}^{\infty}\int_0^t\left[\lambda(u)\frac{[\Lambda(u)]^{i-1}}{(i-1)!}\mathrm{e}^{-\Lambda(u)}\right]*g^{(i)}(u)\,\mathbb{P}\{Y_{i+1}>t-u\}\,\mathrm{d}u\\&=[1-F(t)]+\sum_{i=1}^{\infty}\int_0^t\left[\lambda(u)\frac{[\Lambda(u)]^{i-1}}{(i-1)!}\mathrm{e}^{-\Lambda(u)}\right]*g^{(i)}(u)[1-G(t-u)]\,\mathrm{d}u.\end{aligned} \tag{2.17}$$

Taking the Laplace transform for equation (2.17), we have

$$\begin{aligned}A^*_{\text{resume}}(s)&=\frac{1-f^*(s)}{s}+\frac{1-g^*(s)}{s}\sum_{i=1}^{\infty}[g^*(s)]^i\int_0^{\infty}\lambda(u)\frac{[\Lambda(u)]^{i-1}}{(i-1)!}\mathrm{e}^{-\Lambda(u)}\mathrm{e}^{-su}\mathrm{d}u\\&=\frac{1-f^*(s)}{s}+\frac{[1-g^*(s)]g^*(s)}{s}\sum_{i=1}^{\infty}\int_0^{\infty}\lambda(u)\frac{[\Lambda(u)g^*(s)]^{i-1}}{(i-1)!}\mathrm{e}^{-\Lambda(u)}\mathrm{e}^{-su}\mathrm{d}u\\&=\frac{1-f^*(s)}{s}+\frac{[1-g^*(s)]g^*(s)}{s}\int_0^{\infty}\lambda(u)\mathrm{e}^{-\Lambda(u)}\mathrm{e}^{-su}\sum_{i=1}^{\infty}\frac{[\Lambda(u)g^*(s)]^{i-1}}{(i-1)!}\mathrm{d}u\\&=\frac{1-f^*(s)}{s}+\frac{[1-g^*(s)]g^*(s)}{s}\int_0^{\infty}\lambda(u)\mathrm{e}^{-\Lambda(u)}\mathrm{e}^{-su}\mathrm{e}^{\Lambda(u)g^*(s)}\mathrm{d}u\\&=\frac{1-f^*(s)}{s}+\frac{[1-g^*(s)]g^*(s)}{s}\int_0^{\infty}\lambda(u)\mathrm{e}^{-[1-g^*(s)]\Lambda(u)}\mathrm{e}^{-su}\mathrm{d}u\\&=\frac{1-f^*(s)}{s}+\frac{g^*(s)}{s}\int_0^{\infty}[1-g^*(s)]\lambda(u)\mathrm{e}^{-[1-g^*(s)]\Lambda(u)}\mathrm{e}^{-su}\mathrm{d}u\\&=\frac{1-f^*(s)}{s}+\frac{g^*(s)}{s}f^*_{[1-g^*(s)]\lambda}(s),\end{aligned} \tag{2.18}$$

where $f^*_{c\lambda}(s)=\int_0^{\infty}c\lambda(t)\mathrm{e}^{-c\Lambda(t)}\mathrm{e}^{-st}\mathrm{d}t$, $f(t)=\lambda(t)\mathrm{e}^{-\Lambda(t)}$.

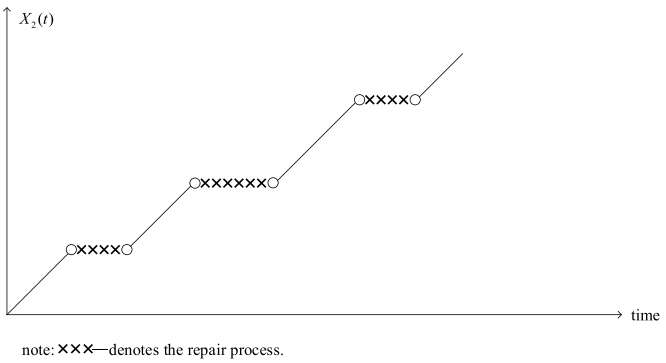


Figure 5. The process of breakdowns and repairs under the resume model.

Similarly, for the interval availability, we have

$$\begin{aligned}
&A_{\text{resume}}\left([t,t+\Delta_0]\right)\\
&=\mathbb{P}\{X_1<\Delta_0\}+\sum_{i=1}^{\infty}\mathbb{P}\left\{\sum_{k=1}^{i}\left(X_k+Y_k\right)\leqslant t<t+\Delta_0<\sum_{k=1}^{i}\left(X_k+Y_k\right)+Y_{i+1}\right\}\\
&=\left[1-F(\Delta_0)\right]+\sum_{i=1}^{\infty}\int_0^t\left[\lambda(u)\frac{\left[\Lambda(u)\right]^{i-1}}{(i-1)!}\mathrm{e}^{-\Lambda(u)}\right]*g^{(i)}(u)\,\mathbb{P}\{Y_{i+1}>t+\Delta_0-u\}\,\mathrm{d}u\\
&=\left[1-F(\Delta_0)\right]+\sum_{i=1}^{\infty}\int_0^t\left[\lambda(u)\frac{\left[\Lambda(u)\right]^{i-1}}{(i-1)!}\mathrm{e}^{-\Lambda(u)}\right]*g^{(i)}(u)\left[1-G(t+\Delta_0-u)\right]\mathrm{d}u.
\end{aligned}\tag{2.19}$$

Taking the Laplace transform for equation (2.19), we have

$$\begin{aligned}
&A^*_{\text{resume}}\left([t,t+\Delta_0]\right)(s)\\
&=\frac{1-F(\Delta_0)}{s}+\frac{1-g^*_{\Delta_0}(s)}{s}\sum_{i=1}^{\infty}\left[g^*(s)\right]^i\int_0^{\infty}\lambda(u)\frac{\left[\Lambda(u)\right]^{i-1}}{(i-1)!}\mathrm{e}^{-\Lambda(u)}\mathrm{e}^{-su}\mathrm{d}u\\
&=\frac{1-F(\Delta_0)}{s}+\frac{\left[1-g^*_{\Delta_0}(s)\right]g^*(s)}{s}\sum_{i=1}^{\infty}\int_0^{\infty}\lambda(u)\frac{\left[\Lambda(u)\,g^*(s)\right]^{i-1}}{(i-1)!}\mathrm{e}^{-\Lambda(u)}\mathrm{e}^{-su}\mathrm{d}u\\
&=\frac{1-F(\Delta_0)}{s}+\frac{\left[1-g^*_{\Delta_0}(s)\right]g^*(s)}{s}\int_0^{\infty}\lambda(u)\mathrm{e}^{-[1-g^*(s)]\Lambda(u)}\mathrm{e}^{-su}\mathrm{d}u\\
&=\frac{1-F(\Delta_0)}{s}+\frac{\left[1-g^*_{\Delta_0}(s)\right]g^*(s)}{s\left[1-g^*(s)\right]}\int_0^{\infty}\left[1-g^*(s)\right]\lambda(u)\mathrm{e}^{-[1-g^*(s)]\Lambda(u)}\mathrm{e}^{-su}\mathrm{d}u\\
&=\frac{1-F(\Delta_0)}{s}+\frac{\left[1-g^*_{\Delta_0}(s)\right]g^*(s)}{s\left[1-g^*(s)\right]}f^*_{[1-g^*(s)]\lambda}(s),
\end{aligned}\tag{2.20}$$

where $g^*_{\Delta_0}(s)=\int_0^{\infty}g(t+\Delta_0)\mathrm{e}^{-st}\mathrm{d}t$.

It is obvious that we have $V_2(t)=X_2(t)=t$ for the virtual age process under the resume model and

$$\mathbb{E}\left[V_2(t)\right]=t.\tag{2.21}$$

Summarizing stochastic point processes related to the two models, we can see that the restart model and resume model are related a renewal point process and an inhomogeneous Poisson process, respectively, if the job processing lifetime is given by $F(t)$. Of course, it is important to emphasize that the exponential distribution is excluded from the scope of job processing lifetime distributions for the two models; otherwise, both models reduce to the same one.

In the rest of the paper, we are only interested in how an interrupted or disrupted job can be continued rather than how the disruptions occur, which lets us focus on two entirely different models: the restart and resume models.

The policy is denoted as π or $\pi(t)$ with some proper subscripts, π_0 and π_1 denote the restart and resume models, respectively, M_i $(i=1,2,\ldots,10)$ represent models $1,2,\ldots,10$, respectively.

3. Derivative models

There are many related derivative models based on both basic models, which result not only from theory, but also follow the intrinsic rules in practice.

(1) Mixed model (denoted as M_1)
This model is set up by introducing a threshold to distinguish the restart and resume periods for the whole mission time, the threshold can be measured by an auxiliary parameter α $(0 \leqslant \alpha \leqslant 1)$ multiplying the total duration of the mission/job/task, that is, the threshold is αd, where the d is total duration of the job. More precisely, we can express the policy as

$$\pi(t) = \begin{cases} \pi_0(t), & \text{if } t \leqslant \alpha d, \\ \pi_1(t), & \text{if } t > \alpha d, \end{cases} \tag{3.1}$$

where t is the cumulative valid mission time counted from the most recent beginning of job processing.

If the job time required is a positive random variable, then the mixed model is defined in terms of the following policy:

$$\pi(t) = \begin{cases} \pi_0(t), & \text{if } t \leqslant d_0, \\ \pi_1(t), & \text{if } t > d_0, \end{cases} \tag{3.2}$$

where the parameter d_0 is a prespecified threshold for the model.

A possible sequence of policies under the mixed model for a job is

$$\begin{gathered} \pi_0(t_1), \pi_0(t_2), \cdots, \pi_0(t_n), \pi_1(t_{n+1}), \pi_1(t_{n+2}), \cdots, \text{ if } n \geqslant 1, \\ \pi_1(t_{n+1}), \pi_1(t_{n+2}), \cdots, \text{ if } n = 0, \end{gathered}$$

where $0 < t_i \leqslant \alpha d,\ i = 1,2,\ldots,n;\ \alpha d < t_{n+j} < d,\ j = 1,2,\ldots,$ for the case of finite mission duration, $0 < t_i \leqslant d_0,\ i = 1,2,\ldots,n;\ d_0 < t_{n+j},\ j = 1,2,\ldots,$ for the case of random mission duration; n is the number of restart policies used before mission completion, it may be finite or infinite. The interrupted events should happen at clock times:

$$\begin{aligned} t_1 < t_1 + t_2 < \cdots < \sum_{i=1}^{n} t_i < \sum_{i=1}^{n} t_i + t_{n+1} \\ < \sum_{i=1}^{n} t_i + t_{n+1} + t_{n+2} < \cdots, \end{aligned}$$

if it is assumed that the negligible time is needed for any interrupted job interval.

The model can be explained practically or results from the age change of products or systems; for example, when an operating product or system has undergone many repairs or replacements, the subsequent repairs cannot update the product completely when the mission duration exceeds a threshold, i.e. the mixed model can be properly used for this scenario.

(2) Mixed model with a random threshold (denoted as M_2)
Similar to the mixed model, this model can be established via introducing a random threshold to distinguish the restart and resume periods in the whole mission time. The threshold can be measured by X, where the positive random variable X satisfies

$$\mathbb{P}\{0 < X \leqslant d\} = 1, \tag{3.3}$$

and the policy can be expressed as

$$\pi(t) = \begin{cases} \pi_0(t), & \text{if } t \leqslant X = x, \\ \pi_1(t), & \text{if } t > X = x, \end{cases} \tag{3.4}$$

where x is a realization of random variable X. A possible sequence of policies under the mixed model with a random threshold for a job is

$$\begin{gathered} \pi_0(t_1|x_1 \leqslant t_1), \pi_0(t_2|x_2 \leqslant t_2), \cdots, \pi_0(t_n|x_n \leqslant t_n), \\ \pi_1(t_{n+1}|x_{n+1} > t_{n+1}), \pi_1(t_{n+2}), \cdots, \text{ if } n \geqslant 1 \\ \pi_1(t_{n+1}|x_{n+1} > t_{n+1}), \pi_1(t_{n+2}), \cdots, \text{ if } n = 0, \end{gathered}$$

where $x_1, x_2, \ldots$ are realizations of X at the interrupted event times $t_1, t_1 + t_2, \ldots, \pi_j(t_i|A_i)$ $(j = 0,1)$ are the policies at time t_i given the condition A_i. Note that the policy tells us that the first policy may be the restart policy with probability $P\{X \geqslant t_1\}$. Once the resume policy is adopted, then the subsequent policies must be resume ones, which is why the model has a random threshold parameter.

The motivation for developing this model comes from scenarios similar to those mentioned in model 1. The special feature of this model is the presence of a random threshold change instant.

(3) Random mixed model (denoted as M_3)
This model can be established by introducing a probability of random choosing a policy at time t within the restart and resume policies, respectively. The corresponding probabilities are denoted as $p(t)$ and $q(t) = 1 - p(t)$; that is, the restart or resume policy is used at the interrupted time t. The corresponding mathematical expression can be given by

$$\mathbb{P}\{\pi(t) = \pi_0(t)\} = p(t),\ \mathbb{P}\{\pi(t) = \pi_1(t)\} = q(t). \tag{3.5}$$

A possible sequence of policies under the random mixed model for a job is

$$\pi_{I_1}(t_1), \pi_{I_2}(t_2), \cdots,$$

where the subscripts $I_1, I_2, \ldots$ are independent random variables with probabilities

$$\mathbb{P}\{I_i = 0\} = p(t_i),\ \mathbb{P}\{I_i = 1\} = q(t_i). \tag{3.6}$$

Note that the random mixed model is very similar to Barlow and Proschan's (1983) model.

The reasons for developing this model come from scenarios similar to those mentioned in models 1 and 2. The unique characteristic of this model is the presence of a random change point process.

(4) Cyclic mixed model (denoted as M_4)
This model can be developed by dividing the whole mission time into several periods and the restart (resume) and resume (restart) policies are adopted alternatively in these periods. The simplest case is when there are two periods in total; in this situation, one case of the model reduces to the mixed model.

A possible sequence of policies under the cyclic mixed model for a job is

$$\begin{aligned}&\pi_0(t_1),\cdots,\pi_0(t_{n_1}),\pi_1(t_{n_1+1}),\cdots\pi_1(t_{n_1+n_2}),\\&\pi_0(t_{n_1+n_2+1}),\cdots,\text{ if } n_1\geqslant 1,\pi_1(t_{n_1+1}),\cdots\pi_1(t_{n_1+n_2}),\\&\pi_0(t_{n_1+n_2+1}),\cdots,\pi_0(t_{n_1+n_2+n_3}),\pi_1(t_{n_1+n_2+n_3+1}),\cdots,\text{ if } n_1=0,\end{aligned}$$

where n_1 is the number of restart policies first used in the restart period before mission completion, n_2 is the number of resume policies first used in the resume period before mission completion, n_3 is the number of restart policies used in the second restart period before mission completion, and so forth.

The background of this model is that the operating product or system undergoes some periodic complete replacements. In this case, the current model may be used to fit the situation properly.

(5) Discounted model (denoted as M_5)
When an interrupted event occurs at time v $(0<v)$, then the new processing begins at a reduced time instant $\alpha_i v$ $(0\leqslant\alpha_i\leqslant c)$ (or other discounted ways), which is similar to the virtual age concept, i.e. the previous processing duration v is equivalent to the processing duration $\alpha_i v$ in the new processing. If it allows more than one interrupted event to occur, then it has, at least, two derivative models on the policy, which are equivalent to the famous models for maintenance: Kijima models I and II (Kijima 1989) for $c=1$. If $c>1$, the model can be thought of as an extended Kijima model. (Note, that we have not distinguished between Kijima models I and II here; the concept model is only introduced, but in the detailed studies, the difference is necessarily considered.)

A possible sequence of policies under the discounted model for a job is shown in figure 6.

The reasons for developing the model is that imperfect repairs occur more frequently in the real world.

(6) Vague model (denoted as M_6)
When an interrupted event occurs at time t_i, the new processing follows either the restart or resume policy, depending on the new processing duration. If the duration is greater than a given threshold, then the new processing is the resume policy; otherwise, it is a restart policy. That is to say, the policy can be determined if the new processing time Δ_i reaches a given threshold value d_0, such that $\Delta_i\geqslant d_0$, i.e. before the new job processing reaches the threshold, we do not know which policy it will follow if $t_i+\Delta_i<d$. This is why we call it a vague model.

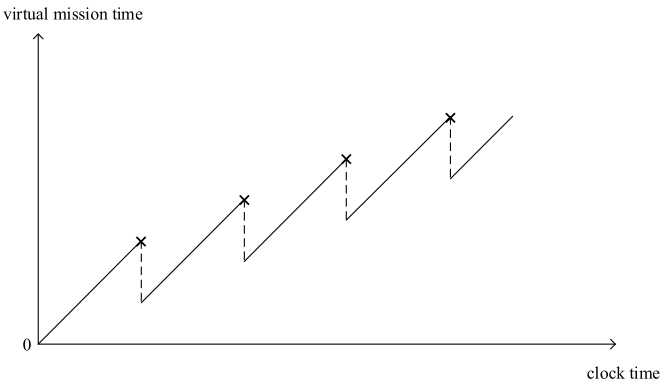


Figure 6. The virtual mission time under the discounted model.

A possible sequence of policies under the vague model for a job is

$$\pi_{J_1}(t_1),\pi_{J_2}(t_2),\cdots,$$

where the subscripts $J_1,J_2,\ldots$ are determined by

$$J_i=\begin{cases}0, & \text{if } \Delta_i<d_0,\\ 1, & \text{if } \Delta_i\geqslant d_0.\end{cases}\quad(i=1,2,\ldots). \tag{3.7}$$

The motivation for introducing the model results from the fact that a perfect replacement cannot be realized for complex systems when the operation lasts for a specified long time. Repairs before and after this specified instant can be treated as 'maximal and minimal repairs', respectively.

(7) Model for limited restart times (denoted as M_7)
This model can be developed by using the policy of limited restart times at the beginning period. After the finite restart policies, the resume policy is used until the job is completed if the job is not completed under the finite restart policies. The policy can be expressed as $\pi_{01}=(n_0,\infty)$, where the subscripts 0 and 1 represent the restart and resume policies, respectively. The nonnegative integer parameter n_0 represents the specified restart times and the infinity is for the unlimited resume policies used.

A possible sequence of policies under the model for a job is

$$\pi_0(t_1),\cdots,\pi_0(t_{n_0}),\pi_1(t_{n_0+1}),\pi_1(t_{n_0+2}),\cdots,\text{ if } n_0\geqslant 1.$$

Note that if $n_0=0$, it implies that the model reduces to a resume one.

The reasons for developing the model are similar to that in model 7, but the threshold specified time is replaced by the number of failures.

(8) Model for limited resume times (denoted as M_8)
Similar to the model for limited restart times, this model can be built by using the policy of limited resume times at the beginning period. After the finite resume policies, the restart policy is used until the job is completed. The policy can be expressed as $\pi_{10}=(m_0,\infty)$, where the nonnegative integer parameter m_0 represents the specified resume times.

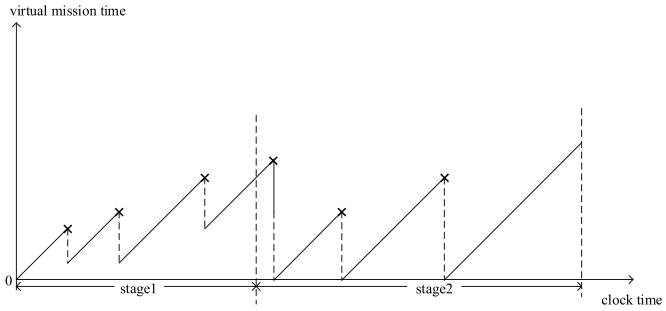


Figure 7. Realization of a virtual mission time under the multi-stage mixed model.

Similarly, a possible sequence of policies under the model for a job is

$$\pi_1(t_1),\cdots,\pi_1(t_{m_0}),\pi_0(t_{m_0+1}),\pi_0(t_{m_0+2}),\cdots, \text{ if } m_0 \geqslant 1.$$

Note that if $m_0 = 0$, it implies that the model reduces to a restart one.

The model can be fitted to situations when minimal repairs cannot be carried out forever for complex systems.

(9) Multi-stage hybrid and discount model (denoted as M_9)
This model can be developed by extending the cyclic mixed model. More precisely, the mission duration is divided into several stages. The discounted model can be used in each stage and the transform information needs to be specified between two adjacent stages. In fact, this model can be thought of as a multi-stage Kijima model.

A possible sequence of policies under a two-stage mixed model for a job is shown in figure 7.

Note that, in figure 5, the transform policy between stages 1 and 2 is the 'keep the same virtual mission time'. Of course, there are many principles or rules that can be used.

The model may fit the situations very well in which each stage can be modeled by a previous model and the mission time contains several stages.

(10) Two-dimensional mixed model (denoted as M_{10})
This model can be built by considering both the elapsed mission time and the proportion of jobs, which is composed of a two-dimensional plane, so that the partition on the plane can form at least two areas, which can result in restart and resume policies in these disjoint areas. Here, the proportion of the job can be scored between the interval [0,1]. In fact, other pair issues affecting the processing of the job can be considered to construct a two-dimensional plane such as cost and time.

Figure 8 is an example of a two-dimensional mixed model, in which the upper area belongs to the resume policy region and the lower area is for the restart policy region. In this case, once the job processing enters the resume area, it stays there until the job is completed.

The motivation for developing the model is to consider two-dimensional index (time, job proportion) $= (t, r(t))$ that forms a plane for decision-making, thus different areas can fit the different situations.

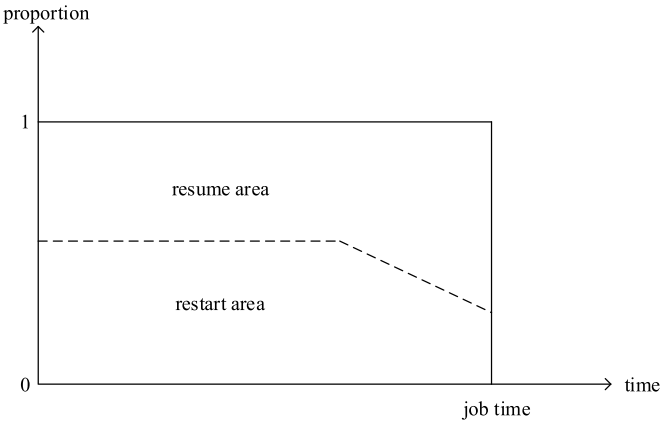


Figure 8. An example of the two-dimensional mixed model with policy regions.

As in section 2, we discuss four issues for each model: (i) failure rate process $\{\lambda_{\text{model } i}(t), t \geqslant 0\}$, (ii) breakdown counting process $\{N_{\text{model } i}(t), t \geqslant 0\}$, (iii) point-wise and interval availabilities $A_{\text{model } i}(t)$ and $A_{\text{model } i}([t, t+\Delta_0])$, and (iv) virtual age process $\{V_{\text{model } i}(t), t \geqslant 0\}$. However, due to limited space, a model-based focus and some difficulty in the paper, we cannot provide analytical results for them, and they will be the focus of our future research. In fact, in general, some processes have randomness rather than deterministic functions, which makes the problem more complicated. For example, under model 8, it has

$$\begin{cases} \lambda_{\text{model 8}}(t) = \lambda_{\text{resume}}(t) I_{\{t \leqslant T_{m_0}\}} + \lambda_{\text{restart}}(t) I_{\{t > T_{m_0}\}}, \\ T_{m_0} \text{ has a pdf } g_{m_0}(t) = \dfrac{[\Lambda(t)]^{m_0}}{m_0!} \lambda(t) \mathrm{e}^{-\Lambda(t)}, \ t \geqslant 0, \end{cases} \tag{3.8}$$

where $\lambda_{\text{model 8}}(t)$ is the failure rate process under model 8 and I_A is an indicator function of event A, i.e. $I_A = 1$ if event A occurs, otherwise, $I_A = 0$.

Of course, there exist other related models, because of limited space, they are omitted here. Readers can extend these models based on the features of their own problems and applications.

4. Relationship among models

Some relationships exist among these 10 models proposed for job processing, including maintenance activities, which may be useful in their related research and applications. In this section, we shall briefly discuss the relationships .

It is not difficult to draw the following conclusions:

$M_1 \supseteq \{\text{Restart, Resume models}\}$, when $d_0 = d$ and $d_0 = 0$, respectively,
$M_1 \subseteq M_2$, when $\mathbb{P}\{X = d_0\} = 1$,
$\{\text{Restart, Resume models}\} \subseteq M_3$, when $p(t) \equiv 1$ and $p(t) \equiv 0$, respectively,
$M_4 \subseteq M_3$, when $p(t) \equiv 1$ during periods 1, 3,..., and $p(t) \equiv 0$ during periods 2, 4,...,

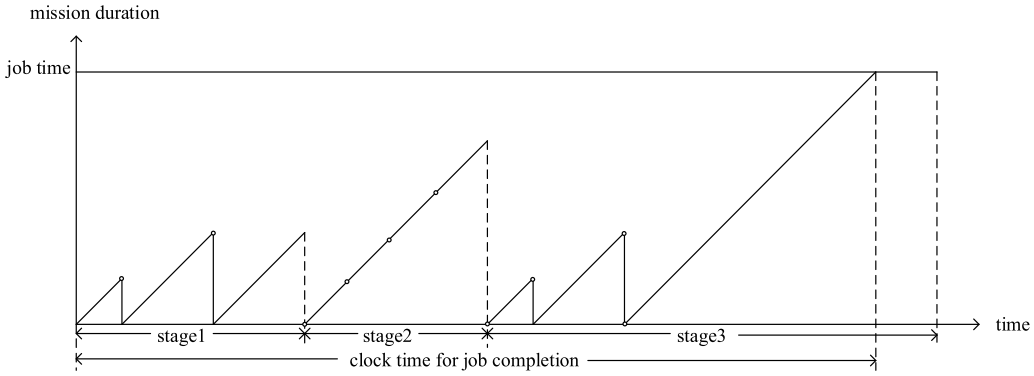


Figure 9. A virtual multi-stage mission duration for a special case.

$M_5 \supseteq \{\text{Restart, Resume models}\}$, when $\alpha = 0$ and $\alpha = 1$, respectively,

$M_6 \supseteq \{\text{Restart, Resume models}\}$, when $d_0 = d$ and $d_0 = 0$, respectively,

$M_7 \supseteq \{\text{Restart, Resume models}\}$, when $n_0 = \infty$ and $n_0 = 0$, respectively,

$M_8 \supseteq \{\text{Restart, Resume models}\}$, when $m_0 = 0$ and $m_0 = \infty$, respectively,

$M_4 \subseteq M_9$ when the number of stages is one.

It is obvious that models 1–9 are for one-dimensional cases and model 10 is for two-dimensional situations.

On the other hand, all these one-dimensional models have some joint subsets under various conditions, which can be used in some concrete situations. For example, for models M_4 and M_9, the transform information between adjacent stages can be specified in terms of the following methods:

$$v_{i+1,0} = \begin{cases} v_{i,\text{end}}, \text{ if adjacent environments are changed slightly,} \\ 0, \text{ if adjacent environments are changed dramatically,} \\ \quad i = 1, 2, \ldots, \\ \alpha_i v_{i,\text{end}}, \text{ if adjacent environments are changed partially,} \end{cases}$$

where $v_{i,\text{end}}$ is a virtual mission duration at the end of stage i,

$v_{i+1,0}$ is a virtual mission duration at the beginning of stage $i+1$,

$0 \leqslant \alpha_1 \leqslant \cdots \leqslant \alpha_i \leqslant 1$, are the coefficients, the smaller α_i is, the larger the different environment is.

If we take $v_{i+1,0} = 0,\ \alpha_i = 0$, for all $i \geqslant 1$, then model M_9 consists of Kijima models 1 and 2 alternatively, and if Kijima models I and II reduce to the restart model and resume model, respectively, then M_9 reduces into model M_4. On the other hand, it is clear to know that $M_9 \supset M_4$, thus $M_9 \cap M_4 \neq \phi$.

The above relationship is shown in figure 9.

5. Conclusion

The restart and resume models are two basic 'element models' in maintenance subjects and they can be used to derive various maintenance models for inspections, diagnoses, repairs and replacements. Four issues, (i) failure rate processes, (ii) breakdown counting processes, (iii) point-wise and interval availabilities, and (iv) virtual age processes, are given under the two basic models. Moreover, 10 derivative-related models have been introduced in this paper and the relationships among them are briefly discussed. In essence, all models proposed in this paper address how to arrange two segments of restarts and resumes. Different arrangements form different policies which generate the corresponding various models. These 10 derivative models can not only enrich the maintenance model bank, which may be related to AI for reliability, but also be used in maintenance optimization problems that might employ the machine learning technique.

We believe that deeper studies on the basic models can not only help us to understand their properties, but also broaden our view on the various related models, especially in the maintenance field. Further research may include: (i) the study of failure rate processes $\{\lambda_{\text{model } i}(t), t \geqslant 0\}$; (ii) the study of breakdown counting process $\{N_{\text{model } i}(t), t \geqslant 0\}$; (iii) the study of related maintenance index processes such as point-wise availability index process $\{A_{\text{model } i}(t), t \geqslant 0\}$ and interval availability index process $\{A_{\text{model } i}([t, t+\Delta_0]), t \geqslant 0\}$, and others, where Δ_0 is a given interval length. Of course, other interesting quantities, such as related probability and mission or job-related characteristics, may also form our further work. Moreover, the related index comparisons among the 10 models are also important for future research.

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Conflict of interest

The authors declare no conflict of interest.

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