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Analysis of Maintenance-Oriented Performance Measures in Virtualised Systems using Semi-Markov Modelling

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1. INTRODUCTION

In recent years, virtualised computing systems have become an integral part of IT infrastructure due to their flexibility, scalability, and efficient resource utilisation. However, prolonged use of software often leads to performance degradation, referred to as software aging. This phenomenon can significantly impact the reliability and availability of the system. To mitigate the effects of aging, effective maintenance strategies such as software rejuvenation are widely adopted.

Several studies have focused on analysing the reliability of virtualised computing systems using the concept of probabilistic modelling. In our earlier work (Kaur and Bhardwaj, 2026), a semi-Markov model was developed to analyse the performance measures such as Mean Time to System Failure(MTSF) and Availability of a virtualised computing system with backup host under the impact of network failures. Although these metrics provides valuable insights into overall system performance, they do not adequately affects the maintenance requirements and operational workload of the system.

The present study focuses on extending performance evaluation by incorporating maintenance-related measures. In particular, the expected number of repairs of shared memory, network, Virtual Machine Monitor(VMM) along with the expected number of rejuvenations are evaluated to provide a better understanding of system behaviour.

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Furthermore, the impact of software aging on the system is modelled using a Weibull distribution where the time-dependent failure rates are considered. This provides a more realistic scenario for the systems in which software aging plays an important role. Therefore, the proposed analysis provides valuable insights into the interplay between reliability and maintenance, thereby, helps in the formation of effective repair and rejuvenation policies for the virtualised computing systems.

2. REVIEW OF LITERATURE

A comprehensive review of existing literature reveals that the significant research has been carried out focusing on software aging and rejuvenation of virtualsied computing systems using stochastic modelling and reliability based-approach. Using Markov chain analysis, these models assess system availability and associated costs, offering insights into optimization strategies (Koutras and Platis, 2020) (Ghobadi and Rashidi, 2021). A non-Markovian model of software rejuvenation has been developed utilizing Markov Regenerative Processes, which allows for multiple concurrent general timers to improve fitting of duration distributions and enable mixed rejuvenation strategies (Carnevali et al., 2022). Also, Stochastic Reward Net(SRN) modelling framework is introduced to evaluate the performance availability and dependability of VM migration as a rejuvenation strategy under bursty workloads (Torquato et al., 2022) (Le, 2020). Also, a distributed autonomous framework is proposed that utilises proactive rejuvenation and innovative load balancing to address software anomalies in cloud applications, enhancing their availability and performance in the face of frequent failures (Di Sanzo et al., 2021) (Avritzer et al., 2022).

A two-stage genetic mechanism for VM migration-based load balancing is proposed, optimizing both current and future VMH loads for improved performance over existing methods (Hung et al., 2021). To predict software aging and resource exhaustion, a k-nearest neighbour(K-NN) algorithm is proposed utilizing static and adaptive thresholding methods to enhance service availability through pre-emptive rejuvenation (Parashivamurthy and Cholli, 2023). To address software aging, a proposed policy combines static analysis of system behavior with dynamic workload adjustments to optimize rejuvenation timing and enhance performance (Bitaraf et al., 2024).

A review of the existing literature indicates that the stochastic modeling techniques have been widely used to analyze the reliability of virtualized computing systems. Most of these studies primarily focus on evaluating reliability-oriented performance measures such as Mean Time to System Failure (MTSF) and system availability.

In this context, (Kaur and Bhardwaj, 2026) developed a semi-Markov model to study the performance of a virtualized computing system with a backup host under the impact of network failures. The analysis was mainly confined to reliability measures, which provide an overall assessment of system performance. However, such measures do not adequately capture the maintenance characteristics and operational workload of the system. In particular, aspects such as the expected number of repairs of critical components (shared memory, network, and Virtual Machine Monitor) and the expected number of rejuvenations have not been sufficiently addressed. These measures are important for understanding system behavior under degradation and for designing effective maintenance strategies.

Therefore, in order to fill the research gap, existing framework is extended by incorporating maintenance-oriented performance measures, so as to provide a more comprehensive evaluation of virtualized computing systems.

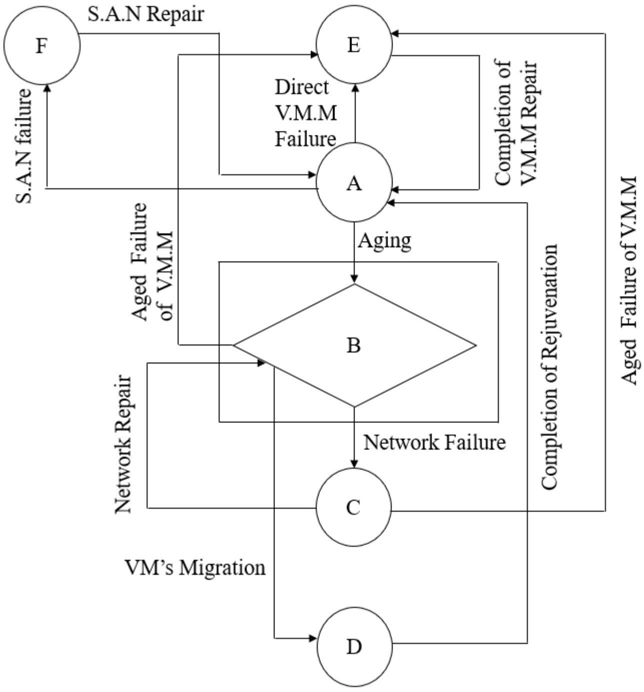

Figure 1: Conceptual Model of the system

The system starts from the robust state A, from which multiple transitions are possible depending on the occurrences of failures and aging. The system may directly experience a shared memory failure, leading to a repair state after which it returns to the normal operating state. Similarly, failure of the Virtual Machine Monitor (VMM) results in a transition to its corresponding repair state, followed by repair to the initial state.

In addition to sudden failures, the system may gradually degrade due to software aging and enter a failure probable state (state B). From this state the system may encounter VMM failure, requiring repair before returning to the normal state. Alternatively, aging may trigger migration of virtual machines to a backup host for rejuvenation purpose. During this migration, the possibility of network failure is also considered, which interrupts the process and leads to transition to repair state. Once the network is repaired, the migration process is resumed and system moves to rejuvention state.

In the absence of network failure, virtual machines are successfully migrated to the backup host, allowing rejuvenation of the VMM on the primary host. After completion of rejuvenation, the system successfully moves to fully operational state A.

3. NOTATIONS AND ASSUMPTIONS

3.1. Notations and symbols

The notations and symbols used in the model are given in Table 1.

3.2. Assumptions of Model

- The computing system consists of two hosts, one host is operating i.e., in active state and the other host is backup host which is in passive state i.e., cold standby state.
- There is a single repair-person/ maintenance engineer who is present in system and cannot fail while performing its duty.
- All VMM rejuvenations and repairs are perfect. All the random variables are statistically independent and follow general distributions.
- The failure of Shared Memory is considered only at the initial state of the system.

Table 1: Notations and symbols

Notations & Symbols		Descriptions
Z_i, j	:	Random variable representing holding time between transitions from S_i to S_j
$g_a(t)/G_a(t)$	:	PDF/CDF of time taken by the system to reach the failure probable zone after aging of V.M.M
$s_c(t)/S_c(t)$	:	PDF/CDF of time taken by the system to complete the rejuvenation process and get back to the robust state
$g_m(t)/G_m(t)$	:	PDF/CDF of time taken by the system to reach the rejuvenation state after migration of VMs from active host to backup host
$m_f(t)/M_f(t)$	:	PDF/CDF of failure time of VMM after aging
$k_f(t)/K_f(t)$	:	PDF/CDF of failure time of VMM
$k_r(t)/K_r(t)$	:	PDF/CDF of repair time of VMM
$v_f(t)/V_f(t)$	:	PDF/CDF of failure time of shared memory
$v_r(t)/V_r(t)$	:	PDF/CDF of repair time of shared memory
$n_f(t)/N_f(t)$	:	PDF/CDF of time taken for a network to enter a failure state during the migration of a Virtual Machine (VM)
$n_r(t)/N_r(t)$	:	PDF/CDF of time taken for a network to reach an aging state after repair
E	:	Set of regenerative states
U	:	Set of up states
γ	:	Failure rate of shared memory
δ	:	Repair rate of shared memory
β	:	Repair rate of V.M.M
b	:	Rate of completion of rejuvenation
λ	:	Failure rate of V.M.M
c	:	Rate at which system reaches failure probable zone
d	:	Rate of rejuvenation after migration
f	:	Failure rate of V.M.M after aging
α	:	Failure rate of network during migration of VM
Ψ	:	Repair rate of network

4. SYSTEM AND STATES DESCRIPTIONS

4.1. State Description

The following are the possible transition states of the system model:

$$S_0 = (H_{1a}, H_{2p}, SAN) \qquad S_1 = (VMM_F, H_{2p}, SAN)$$
$$S_2 = (VMM_{fpz}, H_{2p}, SAN,) \qquad S_3 = (VMM_{rej}, H_{2a}, SAN)$$
$$S_4 = (H_{1a}, H_{2p}, SAN_F) \qquad S_5 = (H_{1a}, H_{2p}, SAN, NF)$$

4.2. State Transition Diagrams

The state transition diagram of the Model are represented by fig.2.

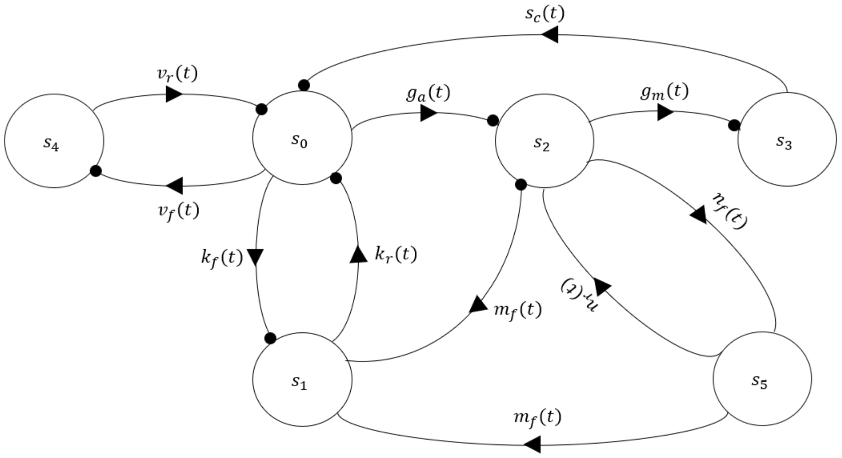

Figure 2: State Transition Diagram

Random Variables utilized in the model development are displayed in Table 2.

Table 2: Random Variables used in the model

Transitions	Descriptions
$S_0 \to S_1$	A random variable with distribution function $K_f(t)$ represents the duration for the VMM of an active host to transition from a running state to a failed state.
$S_0 \to S_2$	A random variable with distribution function $G_a(t)$ represents the duration it takes to reach the failure probable zone after aging.
$S_0 \to S_4$	A random variable with distribution function $V_f(t)$ represents the duration for the shared memory to transition from a running state to a failed state.
$S_1 \to S_0$	A random variable with distribution function $K_r(t)$ denotes the duration for the VMM to transition from a repair state to a robust state.
$S_3 \to S_0$	A random variable with distribution function $S_c(t)$ represents the duration it takes for the system to complete the rejuvenation process and return to a robust state.
$S_4 \to S_0$	A random variable with distribution function $V_r(t)$ denotes the duration for the shared memory to transition from a repair state to a robust state.
$S_2 \to S_1$	A random variable with distribution function $M_f(t)$ represents the duration for the VMM of an active host to reach a failed state after aging.
$S_2 \to S_3$	A random variable with distribution function $G_m(t)$ represents the duration to reach the rejuvenation state after migration of VMs from an active host to a backup host.
$S_2 \to S_5$	A random variable with distribution function $N_f(t)$ represents the duration until the network transitions to a failed state.
$S_5 \to S_2$	A random variable with distribution function $N_r(t)$ represents the duration until the network transitions to an aging state after repair.

Table 2: Random Variables used in the model (continued)

Transitions	Descriptions
$S_5 \to S_1$	A random variable with distribution function $M_f(t)$ represents the duration for the VMM of an active host to reach a failed state after aging and while the network undergoes repair.

4.3. The Transition Probabilities and Mean Sojourn Times

Simple Probabilistic consideration yields the following expression for non-zero elements:

$$p_{i,j} = Q_{i,j}(\infty) = \int\limits_0^\infty q_{i,j}(t)\,dt = \tilde{Q}_{i,j}(0) \tag{1}$$

we get:

$$p_{0,1} = \int_0^\infty k_f(t)\bar{V}f(t)\bar{G}_a(t), dt \qquad p_{0,2} = \int_0^\infty g_a(t)\bar{K}f(t)\bar{V}_f(t), dt$$

$$p_{0,4} = \int_0^\infty v_f(t)\bar{K}f(t)\bar{G}_a(t), dt \qquad p_{1,0} = \int_0^\infty k_r(t), dt$$

$$p_{3,0} = \int_0^\infty s_c(t), dt \qquad p_{4,0} = \int_0^\infty v_r(t), dt$$

$$p_{2,3} = \int_0^\infty g_m(t)\bar{M}_f(t)\bar{N}_f(t), dt \qquad p_{2,1} = \int_0^\infty m_f(t)\bar{G}_m(t)\bar{N}_f(t), dt$$

$$p_{2,5} = \int_0^\infty n_f(t)\bar{M}_f(t)\bar{G}_m(t), dt \qquad p_{5,1} = \int_0^\infty m_f(t)\bar{N}r(t), dt$$

$$p_{5,2} = \int_0^\infty n_r(t)\bar{M}f(t), dt$$

The mean sojourn time in state S_i is given by

$$\mu_i = \int\limits_0^\infty P(T_i > t)dt \tag{2}$$

The mean sojourn times of this model are as follows:

$$\mu_0 = \int\limits_0^\infty \bar{K}_f(t)\bar{V}_f(t)\bar{G}_a(t)dt \qquad \mu_1 = \int\limits_0^\infty \bar{K}_r(t)dt$$

$$\mu_2 = \int\limits_0^\infty \bar{G}_m(t)\bar{M}_f(t)\bar{N}_f(t)dt \qquad \mu_3 = \int\limits_0^\infty \bar{S}_c(t)dt$$

$$\mu_4 = \int\limits_0^\infty \bar{V}_r(t)dt \qquad \mu_5 = \int\limits_0^\infty \bar{M}_f(t)\bar{N}_r(t)dt$$

5. PERFORMANCE MEASURES

5.1. Expected number of repairs of V.M.M

Let, $N_i(t)$ be the expected number of repairs of V.M.M in (0,t] such that the system entered in state S_i at $t = 0$. The set of recursive relations are as follows:

$$N_i(t) = \sum_{\substack{i,j \in E \\ k,l,m... \in (\bar{U} \cap \bar{E})}} [Q_{i,j}(t) + \delta_{i,j,k,l,...} \{Q_{i,j.k}(t) + Q_{i,j.kl}(t) + ...\}] \, [c](\delta_j + N_j(t)) \tag{3}$$

$$; i = 0, 1, 2, 3, 4, 5$$

Taking LST of equation and solving for $\tilde{N}_0(s)$. The number of repairs of V.M.M are given by:

$$N_0 = \lim_{s \to 0} s\tilde{N}_0(s) = \frac{N_{33}}{D_{32}} \tag{4}$$

where,

$$\begin{aligned} N_{33} =& p_{0,1}p_{1,0} + p_{0,2}p_{2,1}p_{1,0} + p_{0,2}p_{2,5}p_{5,1}p_{1,0} - p_{0,1}p_{1,0}p_{2,5}p_{5,2} \\ D_{32} =& (1 - p_{2,5}p_{5,2})(\mu_0 + p_{0,1}\mu_1 + p_{0,4}\mu_4) + p_{0,2}\mu_2 + p_{0,2}p_{2,3}\mu_3 + p_{0,2}p_{2,5}\mu_5 + \\ & (p_{0,2}p_{2,5}p_{5,1} + p_{0,2}p_{2,1})\mu_1 \end{aligned}$$

5.2. Expected number of repairs of Shared Memory

Let, $J_i(t)$ be the expected number of repairs of shared memory in (0,t] such that the system entered in state S_i at $t = 0$. The set of recursive relations are as follows:

$$J_i(t) = \sum_{\substack{i,j \in E \\ k,l,m... \in (\bar{U} \cap \bar{E})}} [Q_{i,j}(t) + \delta_{i,j,k,l,...} \{Q_{i,j.k}(t) + Q_{i,j.kl}(t) + ...\}] \, [s](\delta_j + J_j(t))$$

$$i = 0, 1, 2, 3, 4 \tag{5}$$

Taking LST of equation and solving for $\tilde{J}_0(s)$. The number of repairs of V.M.M are given by:

$$J_0 = \lim_{s \to 0} s\tilde{J}_0(s) = \frac{N_{34}}{D_{32}} \tag{6}$$

where,

$$\begin{aligned} N_{34} =& p_{0,4} - p_{0,4}p_{2,5}p_{5,2} \\ D_{32} =& (1 - p_{2,5}p_{5,2})(\mu_0 + p_{0,1}\mu_1 + p_{0,4}\mu_4) + p_{0,2}\mu_2 + p_{0,2}p_{2,3}\mu_3 + p_{0,2}p_{2,5}\mu_5 + \\ & (p_{0,2}p_{2,5}p_{5,1} + p_{0,2}p_{2,1})\mu_1 \end{aligned}$$

5.3. Expected number of rejuvenations of V.M.M

Let, $C_i(t)$ be the expected number of rejuvenations of V.M.M in (0,t] such that the system entered in state S_i at $t = 0$. The set of recursive relations are as follows:

$$C_i(t) = \sum_{\substack{i,j \in E \\ k,l,m... \in (\bar{U} \cap \bar{E})}} [Q_{i,j}(t) + \delta_{i,j,k,l,...} \{Q_{i,j.k}(t) + Q_{i,j.kl}(t) + ...\}] [s](\delta_j + C_j(t)) \quad ; i = 0, 1, 2, 3, 4, 5. \tag{7}$$

Taking LST of equation and solving for $\tilde{C}_0(s)$. The number of repairs of V.M.M are given by:

$$J_0 = \lim_{s \to 0} s\tilde{C}_0(s) = \frac{N_{35}}{D_{32}} \tag{8}$$

where,

$$\begin{aligned} N_{35} =& p_{0,2}p_{2,3} \\ D_{32} =& (1 - p_{2,5}p_{5,2})(\mu_0 + p_{0,1}\mu_1 + p_{0,4}\mu_4) + p_{0,2}\mu_2 + p_{0,2}p_{2,3}\mu_3 + p_{0,2}p_{2,5}\mu_5 + \\ & (p_{0,2}p_{2,5}p_{5,1} + p_{0,2}p_{2,1})\mu_1 \end{aligned}$$

5.4. Expected number of repairs of network

Let, $F_i(t)$ be the expected number of rejuvenations of V.M.M in (0,t] such that the system entered in state S_i at $t = 0$. The set of recursive relations are as follows:

$$F_i(t) = \sum_{\substack{i,j \in E \\ k,l,m... \in (\bar{U} \cap \bar{E})}} [Q_{i,j}(t) + \delta_{i,j,k,l,...} \{Q_{i,j.k}(t) + Q_{i,j.kl}(t) + ...\}] [s](\delta_j + F_j(t)) \quad ; i = 0, 1, 2, 3, 4, 5. \tag{9}$$

Taking LST of equation and solving for $\tilde{F}_0(s)$. The number of repairs of V.M.M are given by:

$$F_0 = \lim_{s \to 0} s\tilde{F}_0(s) = \frac{N_{35}}{D_{32}} \tag{10}$$

where,

$$\begin{aligned} N_{35} =& p_{0,2}p_{2,5}p_{5,2} \\ D_{32} =& (1 - p_{2,5}p_{5,2})(\mu_0 + p_{0,1}\mu_1 + p_{0,4}\mu_4) + p_{0,2}\mu_2 + p_{0,2}p_{2,3}\mu_3 + p_{0,2}p_{2,5}\mu_5 + \\ & (p_{0,2}p_{2,5}p_{5,1} + p_{0,2}p_{2,1})\mu_1 \end{aligned}$$

6. RESULTS AND DISCUSSIONS

A set of hypothetical numerical values are assigned to different parameters as outlined in Table 3.

Table 3: Data Set

Parameters	Values
Rejuvenation rate(d)	0.1 to 0.5
Degradation rate(c)	0.03 and 0.05
Failure rate of shared memory(γ)	0.0002 and 0.0007
Repair rate of shared memory(δ)	0.295 and 0.695
Repair rate of V.M.M(β)	0.695 and 0.95
Rate of completion of rejuvenation(b)	0.0495
Direct Failure rate of V.M.M(λ)	0.002 and 0.005
Aged failure rate of V.M.M(f)	0.3 and 0.5
Rate of Network failure(α)	0.0003 and 0.0007
Rate of Network repair(ψ)	0.175 and 0.795

Suppose that the different random variables included in the model follows Weibull distribution with different parameters. Let the probability density function:

$$\begin{aligned} g_a(t) =& c\eta t^{\eta-1}\exp(-ct^{\eta}) & s_c(t) =& b\eta t^{\eta-1}\exp(-bt^{\eta}) & v_f(t) =& \gamma\eta t^{\eta-1}\exp(-\gamma t^{\eta}) \\ v_r(t) =& \delta\eta t^{\eta-1}\exp(-\delta t^{\eta}) & k_f(t) =& \lambda\eta t^{\eta-1}\exp(-\lambda t^{\eta}) & k_r(t) =& \beta\eta t^{\eta-1}\exp(-\beta t^{\eta}) \\ g_m(t) =& d\eta t^{\eta-1}\exp(-dt^{\eta}) & m_f(t) =& f\eta t^{\eta-1}\exp(-ft^{\eta}) & n_f(t) =& \alpha\eta t^{\eta-1}\exp(-\alpha t^{\eta}) \\ n_r(t) =& \psi\eta t^{\eta-1}\exp(-\psi t^{\eta}) \end{aligned}$$

$$\begin{aligned}
N_{33} &= \left(\frac{c}{\lambda+\gamma+c}\right)\left(\frac{f}{f+d+\alpha}\right)+\left(\frac{\lambda}{\lambda+\gamma+c}\right)+\left(\frac{cf\alpha}{(\lambda+\gamma+c)(d+f+\alpha)(\psi+f)}\right)\\
&\quad -\left(\frac{(\lambda\alpha\psi)}{(\lambda+\gamma+c)(d+f+\alpha)(\psi+f)}\right)\\
N_{34} &= \left(\frac{\gamma}{c+\lambda+\gamma}\right)\left(1-\frac{\alpha\psi}{(d+f+\alpha)(\psi+f)}\right)\\
N_{35} &= \left(\frac{c}{c+\lambda+\gamma}\right)\left(\frac{\alpha\psi}{(d+f+\alpha)(\psi+f)}\right)\\
N_{36} &= \left(\frac{c}{c+\lambda+\gamma}\right)\left(\frac{d}{d+f+\alpha}\right)
\end{aligned}$$

$$\begin{aligned}
D_{32} = \Gamma\left(\frac{\eta+1}{\eta}\right)&\Bigg[\left(1-\frac{\alpha\psi}{(d+f+\alpha)(\psi+f)}\right)\left(\frac{\lambda+\gamma+c}{(\lambda+\gamma+c)^{\frac{\eta+1}{\eta}}}\right)\\
&+\left(\frac{\lambda}{c+\lambda+\gamma}\right)\left(\frac{\beta}{\beta^{\frac{\eta+1}{\eta}}}\right)+\left(\frac{\gamma}{c+\lambda+\gamma}\right)\left(\frac{\delta}{\delta^{\frac{\eta+1}{\eta}}}\right)\\
&+\left(\frac{c}{(c+\lambda+\gamma)(d+f+\alpha)}\right)\left[\left(\frac{\alpha(\psi+f)}{(\psi+f)^{\frac{\eta+1}{\eta}}}\right)+\left(\frac{bd}{b^{\frac{\eta+1}{\eta}}}\right)+\left(\frac{f\alpha\beta}{(\psi+f)\beta^{\frac{\eta+1}{\eta}}}\right)\right]\Bigg]\\
&+\left(\frac{c(d+f+\alpha)}{(\lambda+\gamma+c)(d+f+\alpha)^{\frac{\eta+1}{\eta}}}\right)
\end{aligned}$$

In this study, Weibull distribution is considered as it is suitable for modelling system failures and aging characteristics. The analysis reveals that the expected number of repairs of V.M.M, shared memory and network increases with an increase in failure rate parameters i.e., direct failure rate (λ) from 0.002 to 0.005, the VMM aged failure rate (f) from 0.5 to 0.7, the shared memory failure rate (γ) from 0.0002 to 0.0007, and the network failure rate (α) from 0.0003 to 0.0007. This leads to higher system vulnerability and maintenance requirements. On the other hand, an increase in repair rates of V.M.M (β) from 0.695 to 0.95, shared memory (δ) from 0.295 to 0.695 and network (ψ) from 0.175 to 0.795 reduces the mean sojourn times in failed states, thereby, improving system performance. In addition, higher expected number of rejuvenations leads to trigger more preventive maintenance actions reflecting faster system progression to aging state. Conversely, an increase in the rejuvenation rate faciliates faster completion of the rejuvenation process and the system returns to robust state.

7. CONCLUSION

The present study provides the performance evaluation of a virtualised computing system sharing a common storage area network with backup host. Unlike earlier analysis limited to Mean Time to System Failure(MTSF) and availability, this work extends the models by calculating maintenance-oriented performance measures such as expected number of repairs of shared memory, network, and virtual machine monitor(VMM), along with the expected number of rejuvenations.

Furthermore, the study shows that higher rejuvenation rates reduce the time spent in degraded states, thereby improving system performance, whereas efficient repair mechanisms minimize downtime and maintenance burden. These findings emphasize the importance of appropriately balancing failure rates, repair efficiency, and rejuvenation policies.

Overall, the proposed model provides valuable insights for system designers and administrators in optimizing maintenance strategies, reducing operational costs, and enhancing system reliability. The integration of aging-aware distributions and maintenance-based performance measures makes the analysis more realistic and applicable to modern virtualized computing environments.

Further research may also explore the inclusion of dynamic rejuvenation policies, where rejuvenation strategies are based on real-time system conditions rather than fixed rates. In addition, the model can be extended by incorporating cost analysis associated with repairs, rejuvenation, and downtime, enabling optimization of maintenance strategies from an economic perspective.

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