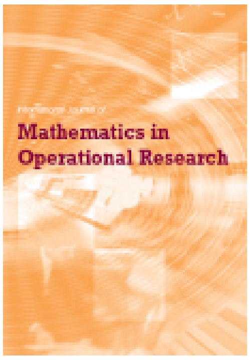

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RAMD approach to performance estimation of fog-to-fog collaboration using software-defined networking

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Abstract: The software-defined networking (SDN) is subject to a variety of adversarial assaults due to its logically centralised design. These assaults have the potential to damage the managed network's performance, or perhaps bring it down in the worst-case scenario. As a result, SDN performance must be examined and estimated in order to determine its dependability, strength, and efficacy. This study aimed to increase SDN dependability, reliability, maintainability, availability, and metrics like MTBF and MTTF by boosting dependability, reliability, maintainability, and availability. The Markovian birth-death process is used to construct the system regulating the differential difference equation from the state transition diagram for modelling and analysis. The rates of repair and failure of each subsystem are exponentially distributed and statistically independent. For several subsystems of the system, the findings for dependability, reliability, maintainability, and availability, all of which are crucial to system performance, have been acquired and shown in figures and tables. The SDN's performance was evaluated using the numerical data gathered. Furthermore, the results of this study reveal that the highest system performance and dependability may be achieved when the overall system failure rate is low.

Keywords: reliability; availability; collaboration; software-defined network.

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1 Introduction

Cloud computing enabled users to access computing resources on demand via the internet. It provides numerous advantages to businesses, including cost reduction, security, and data loss prevention. Despite its benefits, the cloud has drawbacks such as high latency, data theft, and the fact that it can only be used with an internet connection. Fog computing, on the other hand, employs edge devices to perform processing, storing, and communication with IoTs before routing it to the cloud via the internet. It solves the latency problem in the cloud because edge devices are closer to users, the distributed architecture makes it more secure, and enables many communication protocols, making failure rate very low. In addition to the demands of emerging IoT technologies; smart hospitals and intelligent transportation systems (ITS), all of which for processing and data exchange need ultra-low latency. Fog computing is a novel approach that aims to satisfy the needs.

In the aforementioned delay-sensitive applications, data processing latency is greatly reduced by addressing computing needs in fog nodes rather than transmitting huge volumes of data to the cloud. As promising as fog computing appears to be, fog nodes can be easily overwhelmed in a busy location with a plethora of IoTs; hence, fog-to-fog collaboration idea is established to achieve minimal latency for delay sensitive requests.

When a node is overburdened or unable to process user requests, it can collaborate with a neighbouring node to accomplish the task through service offloading. The two major decisions in service offloading are: the tasks to be offloaded and where to offload. The latter is particularly significant because it impacts the system's quality of service (QoS). The offloading destination on the other hand, is chosen using either static or dynamic approaches. A dedicated offloading node is selected in advance for each node in static method, while a favourable offloading node within the system's available fog nodes depending on real-time status is selected in the dynamic approach. There are two approaches to the dynamic method: centralised and distributed. A central controller choses the offloading node in centralised method, whereas nodes share status report, such that overloaded node selects the offloading node itself in distributed method.

Despite the benefits of distributed approaches, some researchers continue to use centralised approaches to address specific issues. For example, software defined networking (SDN) promise of guaranteed bandwidth and minimal latency due to its knowledge of network topology entices researchers to use centralise SDN approach to provide latency-related solutions.

However, the fact that fog collaboration otherwise referred to as federation of fog nodes is a new trend in fog computing research, hence there are still not many studies, there is need to study the reliability analysis of the fog collaboration architectures introduced.

RAMD is a logistical technique for assessing the strength, effectiveness, and performance of equipment at various levels. It ensures system safety and operation problems and identifies which of the system's units, components, or subsystems require adequate maintenance. Reliability, availability, maintainability and dependability (RAMD) management is critical to a company's success. These four measures of system strength, effectiveness, and performance can be used to forecast system speed, product quality, and volume production output.

The paper is organised as follows: Section 2 provide detailed literature review of RAMD models. Materials and methodology of the study are contained in Section 3. Section 4 provides the SDN description. Formulations of the RAMD models are provided in Section 5. The results of our formulations are presented in Section 6 and paper concluded in Section 7.

2 Literature review

Researchers have used a variety of approaches to assess reliability measures in the literature. Das et al. (2020) proposed a technique for estimating the reliability of computational grid. Deepakraj and Raja (2021) developed Markov chain optimisation technique for performance measure of residual energy, energy consumption and delay for routing efficiency in wireless sensor.

Rani and Suri (2021) present stochastic measure in grid computing based on probabilistic scheduling approach. Saini et al. (2021) developed models for availability analysis of data centre using Markovian birth-death process. Tyagi et al. (2022) developed reliability models for performance study and effectiveness of open source software system.

The research reviewed above identified several methods for improving the SDN's functionality. It is clear that a significant amount of research has been done in the direction of SDN Fog collaboration. According to the literature review in Table 1, nothing is known about RAMD in fog-to-fog collaboration utilising SDN in terms of dependability and performance evaluation. Nonetheless, new models with a substantiated and sufficient assessment is obliged. As a result, an attempt has been made in this paper to examine fog-to-fog collaboration utilising SDN in terms of RAMD. To the authors' little knowledge, no RAMD in fog-to-fog collaboration utilising SDN. As a consequence, the current study was intended to fill a research gap.

Table 1 Brief review on RAMD

Author	*Year*	*Reliability metric studied*	*Objective/finding*	*Methodology*
Aggarwal et al.	(2017)	RAMD	To identify the critical component of the system	Markovian birth-death
Aggarwal et al.	(2016)	RA	To enhance the productivity of skim milk powder system	Markov birth-death process
Aggarwal et al.	(2015)	RAMD	To measure and improve the performance of skim milk powder production system of a dairy plant under real working conditions/chiller and cream separator is the most critical from maintenance point of view	Markov birth-death process
Kumar et al.	(2022)	RAMD	Centrifugal pump and power supply units are the most critical components as far as reliability and maintainability aspects	Markovian birth-death
Corvaro et al.	(2017)	RAM	Assessing the operational performance of a reciprocating compressor system package installed and used in the oil and gas' industries	
Choudhary et al.	(2019)	RAM	Critical subsystem from an availability point of view	Markovian birth-death
Dahiya et al.	(2019)	RAM	To evaluate the performance of the sugar plant	Markovian birth-death
Garg	(2014)	RAM	For finding the critical component of the system which affects the system performance	PSO and fuzzy methodology
Goyal et al.	(2019)	RAMD	To analyse the performance	Markovian birth–death process
Gupta et al.	(2021)	RAMD	To find critical component of system so that proper maintenance strategies	Markovian birth–death process
Jagtap et al.	(2021)	RAM	The boiler feed pump affects the system availability at most, while the failure of deaerator affects it least.	Particle swamp optimisation (PSO)
Jakkula et al.	(2022)	RAM	Estimation of the performance of the equipment	Markovian birth-death
Kumar et al.	(2017)	RA	To evaluate various reliability measures like availability, reliability, mean time to failure and profit function	supplementary variable technique, Laplace transformation and Gumbel-Hougaard family of copula
Kumar and Tewari	(2018)	RAM	Investigates the various factors which influence the overall availability of the manufacturing plant	Review
Kumar et al.	(2020a)		Investigate the availability and profit of power generation systems established in sewage treatment plants	

Table 1 Brief review on RAMD (continued)

Author	*Year*	*Reliability metric studied*	*Objective/finding*	*Methodology*
Kumar et al.	(2020b)	RAM	To improve the operational performance of a soft water treatment and supply plant/plant availability decline	Reviews
Malkawi	(2013)	RAMP	To promote the interest of researchers to develop more specific guidelines for the production of SW systems with well-defined RAMP qualities	Reviews
Patil et al.	(2021)	RAM	Critical subsystems from reliability, maintainability, and availability point of view are identified	Markov chain
Reena and Basotia	(2020)	RM	Sulphited syrup section is highly sensitive from reliability point of view	Markov birth–death process
Saini and Kumar	(2019)	RAMD	To analyse the application of reliability, availability, maintainability and dependability in identification of most sensitive subsystem of evaporation system in sugar plant	Markov birth–death process
Sanusi and Yusuf	(2021)	RAMD	To explore computer-based test system reliability indices using a RAMD technique at the component/subcomponent level	Markov birth-death process
Saraswat and Yadava	(2008)	RAMS	To provide an overview of RAMS engineering in industry and research	Reviews much of the literature on RAMS
Tsarouhas	(2020)	RAM	To implement the Six Sigma (SS) strategy in a bag sector under actual operating circumstances	Pareto analysis, histograms and descriptive statistics
Tsarouhas	(2018a)	RAM	There is no correlation between the time between failures and the TTRs for the wine packaging line	failures data
Tsarouhas	(2018b)	RAM	Two machines with the most frequent failures and lowest availabilities are the forming/dosing machine, and the wrapping machine	Failure data
Velmurugan et al.	(2019)	RAM	To analyses the maintenance activity in a small and medium sized enterprise (SME) industry and suggest best maintenance management policy of the given working environment	Markov analysis

3 Material and methods

3.1 Reliability function

The chance that a system/machine will be up and running throughout a period of time t is defined as reliability. Thus, reliability $R(t) = Pr\{T > t\}$, where T is the time when the system is down and not running with $R(t) \geq 0$, $R(t) = 1$. [For a full description, see Ebeling (2000)]. Thus,

$$R(t) = \int_{t}^{\infty} f\left(t_0\right) dt_0 \tag{1}$$

and

$$R(t) = e^{-\lambda t} \tag{2}$$

for exponentially distributed rate of failure

3.2 Availability function

Ebeling (2000) defined availability as the follows:

$$A(t) = \lim A(T) = \frac{MTBF}{MTBF + MTTR} \tag{3}$$

3.3 Maintainability

According to Ebeling (2000), system maintainability is defined as:

$$M(t) = P(T \leq t) = 1 - e^{\left(\frac{-t}{MTTR}\right)} = 1 - e^{-\mu t} \tag{4}$$

where μ is the constant system's repair rate.

3.4 Dependability

Dependability is a metric given by

$$D_{\min} = 1 - \left(\frac{1}{d-1}\right)\left(e^{-\log(d)/d-1} - e^{-d\log(d)/d-1}\right) \tag{5}$$

where

$$d = \frac{\mu}{\theta} = \frac{MTBF}{MTTR} \tag{6}$$

3.5 MTBF

The average time between the failures is known as MTBF. It is usually expressed in hours. As the MTBF increases, so does the system's reliability. The MTBF is given by

$$MTBF = \int_0^\infty R(t)dt = \int_0^\infty e^{-\theta t} dt = \frac{1}{\theta}. \tag{7}$$

3.6 MTTR

The reciprocal of the system repair rate is specified as MTTR given by

$$MTTR = \mu^{-1} \tag{8}$$

where μ is the system's repair rate.

3.7 Exponential distribution

A random variable X is said to obey an exponential distribution with parameter $\theta > 0$, if its probability density function is given by:

$$f(x, \theta) = \begin{cases} \theta e^{-\theta x}, & \text{if } x \geq 0 \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

3.8 Constant failure rate

The constant hazard rate function can be written as follows:

$$F(t) = \int_0^\infty f(t)dt \tag{10}$$

where θ is constant with probability density function, with $F(t) = 1 - e^{-\theta t}$ and $R(t) = e^{-\theta t}$.

4 Description of the proposed SDN

The system is depicted as having three controllers, a supervisor controller and two local controllers. The supervisor controller manages the load among the two local controllers, in other words it makes collaboration possible. The switches s1 to s8 located on different levels are used for data forwarding between the fog nodes. Node 1 to node 8 denotes the available fog nodes considered, which may seek to collaborate with one another.

Figure 1 Reliability block diagram of SDN (see online version for colours)

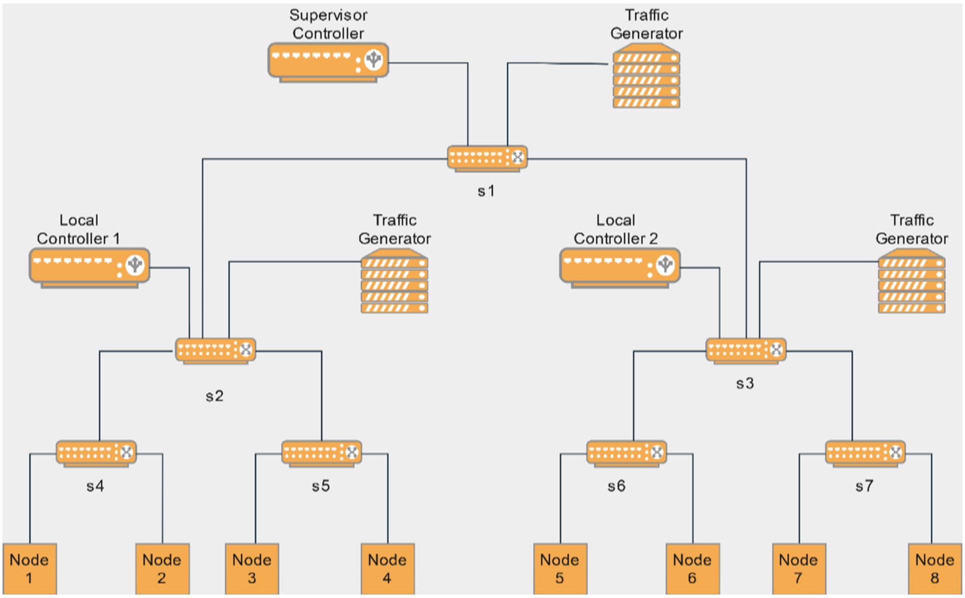
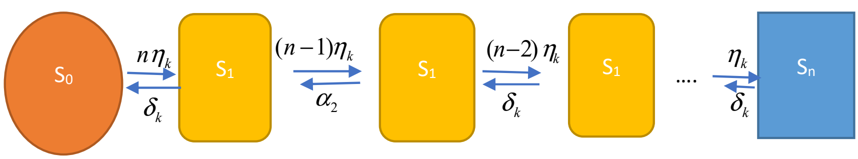


Figure 2 Transition diagram of SDN (see online version for colours)



5 RAMD models formulation

In this section, Markov birth-death process is used develop the Chapman-Kolmogorov differential equations through the transition diagram in Figure 2 of each subsystem.

5.1 Notations

t variable representing time

η_1 and δ_1 stand for rate of failure and repair of unit in subsystem 1

η_2 and δ_2 stand for rate of failure and repair of unit in subsystem 2

η_3 and δ_3 stand for rate of failure and repair of unit in subsystem 3

η_4 and δ_4 stand for rate of failure and repair of unit in subsystem 4

η_5 and δ_5 stand for rate of failure and repair of unit in subsystem 5

η_6 and δ_6 stand for rate of failure and repair of unit in subsystem 6

$h_k(t)$ stand for probability that the system sojourn in state S_k, $k = 0, 1, 2, 3, 4, 5, 6, 7$.

$$\vartheta_k = \frac{\eta_k}{\delta_k}$$

5.2 *RAMD formulation of subsystem A*

Subsystem A consists of eight identical nodes running in active parallel having the same rate of failure and repair. System failure with respect of subsystem A occurs whenever the entire nodes failed. With $n = 8$ and $k = 1$, the system of first order differential difference equation using Figure 2 are:

$$\frac{d}{dt}h_0(t) = -8\eta_1 h_0(t) + \delta_1 h_1(t) \tag{11}$$

$$\frac{d}{dt}h_1(t) = -(7\eta_1 + \delta_1)h_1(t) + 8\eta_1 h_0(t) + \delta_1 h_2(t) \tag{12}$$

$$\frac{d}{dt}h_2(t) = -(6\eta_1 + \delta_1)h_1(t) + 7\eta_1 h_1(t) + \delta_1 h_3(t) \tag{13}$$

$$\frac{d}{dt}h_3(t) = -(5\eta_1 + \delta_1)h_3(t) + 6\eta_1 h_2(t) + \delta_1 h_4(t) \tag{14}$$

$$\frac{d}{dt}h_4(t) = -(4\eta_1 + \delta_1)h_4(t) + 5\eta_1 h_3(t) + \delta_1 h_5(t) \tag{15}$$

$$\frac{d}{dt}h_5(t) = -(3\eta_1 + \delta_1)h_5(t) + 4\eta_1 h_4(t) + \delta_1 h_6(t) \tag{16}$$

$$\frac{d}{dt}h_6(t) = -(2\eta_1 + \delta_1)h_6(t) + 3\eta_1 h_5(t) + \delta_1 h_7(t) \tag{17}$$

$$\frac{d}{dt}h_7(t) = -(\eta_1 + \delta_1)h_7(t) + 2\eta_1 h_6(t) + \delta_1 h_8(t) \tag{18}$$

$$\frac{d}{dt}h_8(t) = -\delta_1 h_8(t) + \eta_1 h_7(t) \tag{19}$$

Solving (11) to (19) in steady state to obtain the following state probabilities

$$h_1(t) = 8\vartheta_1 h_0(t) \tag{20}$$

$$h_2(t) = 56\vartheta_1^2 h_0(t) \tag{21}$$

$$h_3(t) = 336\vartheta_1^3 h_0(t) \tag{22}$$

$$h_4(t) = 1680\vartheta_1^4 h_0(t) \tag{23}$$

$$h_5(t) = 6720\vartheta_1^5 h_0(t) \tag{24}$$

$$h_6(t) = 20160\vartheta_1^6 h_0(t) \tag{25}$$

$$h_7(t) = 40320\vartheta_1^7 h_0(t) \tag{26}$$

$$h_8(t) = 40320\vartheta_1^8 h_0(t) \tag{27}$$

The normalising condition for this analysis is,

$$h_0(\infty) + h_1(\infty) + h_2(\infty) + h_3(\infty) + h_4(\infty) + h_5(\infty) + h_6(\infty) + h_7(\infty) + h_8(\infty) = 1 \tag{28}$$

substituting (20)–(27) in (28) to obtain the initial probability below

$$h_0(\infty) = \frac{1}{\begin{pmatrix} 1 + 8\vartheta_1 + 56\vartheta_1^2 + 336\vartheta_1^3 + 1680\vartheta_1^4 + 6720\vartheta_1^5 \\ +20160\vartheta_1^6 + 40320\vartheta_1^7 + 40320\vartheta_1^8 \end{pmatrix}} \tag{29}$$

The availability of subsystem *A* is

$$A_{\vartheta 1}(\infty) = h_0(\infty) + h_1(\infty) + h_2(\infty) + h_3(\infty) + h_4(\infty) + h_5(\infty) + h_6(\infty) + h_7(\infty) \tag{30}$$

Substituting (20)–(29) in (30), the expression for the availability of subsystem A in (30) is

$$A_{\vartheta 1}(\infty) = \frac{1 + 8\vartheta_1 + 56\vartheta_1^2 + 336\vartheta_1^3 + 1680\vartheta_1^4 + 6720\vartheta_1^5 + 20160\vartheta_1^6 + 40320\vartheta_1^7}{\begin{matrix} 1 + 8\vartheta_1 + 56\vartheta_1^2 + 336\vartheta_1^3 + 1680\vartheta_1^4 + 6720\vartheta_1^5 + 20160\vartheta_1^6 \\ +40320\vartheta_1^7 + 40320\vartheta_1^8 \end{matrix}} \tag{31}$$

From equations (2)–(8), the reliability, maintainability, dependability ratio and dependability of subsystem A are listed below

$$R_{\vartheta 1}(t) = e^{-\eta_1 t} \tag{32}$$

$$M_{\vartheta 1}(t) = 1 - e^{-\eta_1 t} \tag{33}$$

For the subsystem *A*

$$d = \frac{1.2}{0.025} = 48 \tag{34}$$

Substituting (58) into (56) we've

$$D_{\vartheta 1} = 1 - \left(\frac{1}{48 - 1}\right)\left(e^{-\frac{Ln 48}{48-1}} - e^{-\frac{48\, Ln 48}{48-1}}\right) = 0.980814 \tag{35}$$

5.3 *RAMD formulation of subsystem B*

Subsystem B consists of four identical switches running in active parallel having the same rate of failure and repair. System failure with respect of subsystem B occurs whenever the entire switch failed. With $n = 4$ and $k = 2$, the system of first order differential difference equation using Figure 2 are:

$$\frac{d}{dt}h_0(t) = -4\eta_2 h_0(t) + \delta_2 h_1(t) \tag{36}$$

$$\frac{d}{dt}h_1(t) = -(3\eta_2 + \delta_2)h_1(t) + 4\eta_2 h_0(t) + \delta_2 h_2(t) \tag{37}$$

$$\frac{d}{dt}h_2(t) = -(2\eta_2 + \delta_2)h_2(t) + 2\eta_2 h_1(t) + \delta_2 h_3(t) \tag{38}$$

$$\frac{d}{dt}h_3(t) = -(\eta_2 + \delta_2)h_3(t) + 2\eta_2 h_2(t) + \delta_2 h_4(t) \tag{39}$$

$$\frac{d}{dt}h_4(t) = -\delta_2 h_4(t) + \eta_2 h_3(t) \tag{40}$$

Solving (36) to (40) in steady state to obtain the following state probabilities

$$h_1(\infty) = 4\vartheta_2 h_0(\infty) \tag{41}$$

$$h_2(\infty) = 12\vartheta_2^2 h_0(\infty) \tag{42}$$

$$h_3(\infty) = 24\vartheta_2^3 h_0(\infty) \tag{43}$$

$$h_4(\infty) = 24\vartheta_2^4 h_0(\infty) \tag{44}$$

The normalising condition for this analysis is,

$$h_0(\infty) + h_1(\infty) + h_2(\infty) + h_3(\infty) + h_4(\infty) = 1 \tag{45}$$

Using (41)–(44) in (48) to obtain the initial probability below

$$h_0(\infty) = \frac{1}{\left(1 + 4\vartheta_2 + 12\vartheta_2^2 + 246\vartheta_2^3 + 24\vartheta_2^4\right)} \tag{46}$$

The availability of subsystem B is

$$A_{\vartheta_2}(\infty) = h_0(\infty) + h_1(\infty) + h_2(\infty) + h_4(\infty) \tag{47}$$

Substituting (41)–(45) and (46) in (47), the expression for the availability of subsystem B is

$$A_{\vartheta 2}(\infty) = \frac{1 + 4\vartheta_2 + 12\vartheta_2^2 + 24\vartheta_2^3}{1 + 4\vartheta_2 + 12\vartheta_2^2 + 24\vartheta_2^3 + 24\vartheta_2^4} \tag{48}$$

From equations (2)–(8), the reliability, maintainability, dependability ratio and dependability of subsystem B are

$$R_{\vartheta 2}(t) = e^{-\eta_2 t} \tag{49}$$

$$M_{\vartheta 2}(t) = 1 - e^{-\eta 2t} \tag{50}$$

$$d = \frac{0.82}{0.005} = 164 \tag{51}$$

$$D_{S2} = 1 - \left(\frac{1}{164-1}\right)\left(e^{-\frac{Ln164}{164-1}} - e^{-\frac{164\,Ln164}{164-1}}\right) = 0.994428 \tag{52}$$

5.4 RAMD formulation of subsystem C

Subsystem C consists of two identical switches running in active parallel having the same rate of failure and repair. System failure with respect of subsystem C occurs whenever the entire switch failed. With n = 2 and k = 3, the system of first order differential difference equation using Figure 2 are:

$$\frac{d}{dt}h_0(t) = -2\eta_3 h_0(t) + \delta_3 h_1(t) \tag{53}$$

$$\frac{d}{dt}h_1(t) = -(\eta_3 + \delta_3)h_1(t) + 2\eta_3 h_0(t) + \delta_3 h_2(t) \tag{54}$$

$$\frac{d}{dt}h_2(t) = -\delta_3 h_3(t) + \eta_3 h_2(t) \tag{55}$$

Solving (53) to (55) in steady state to obtain the following state probabilities

$$h_1(\infty) = 2\vartheta_3 h_0(\infty) \tag{56}$$

$$h_2(\infty) = 2\vartheta_3^2 h_0(\infty) \tag{57}$$

The normalising condition for this analysis is,

$$h_0(\infty) + h_1(\infty) + h_2(\infty) = 1 \tag{58}$$

Using (56)–(57) in (58) to obtain the initial probability below

$$h_0(\infty) = \frac{1}{\left(1 + 2\vartheta_3 + 2\vartheta_3^2\right)} \tag{59}$$

The availability of subsystem C is

$$A_{\vartheta 3}(\infty) = h_0(\infty) + h_1(\infty) \tag{60}$$

Substituting (56)–(57) and (59) in (60), the expression for the availability of subsystem C is

$$A_{\vartheta 3}(\infty) = \frac{1 + 2\vartheta_3}{1 + 2\vartheta_3 + 2\vartheta_3^2} \tag{61}$$

From equations (2)–(8), the reliability, maintainability, dependability ratio and dependability of subsystem C are

$$R_{\vartheta 3}(t) = e^{-\eta_3 t} \tag{62}$$

$$M_{\vartheta 3}(t) = 1 - e^{-\eta_3 t} \tag{63}$$

$$d = \frac{0.78}{0.0037} = 211 \tag{64}$$

$$D_{S3} = 1 - \left(\frac{1}{211-1}\right)\left(e^{-\frac{Ln211}{211-1}} - e^{-\frac{211\,Ln211}{211-1}}\right) = 0.995380 \tag{67}$$

5.5 *RAMD formulation of subsystem D*

Subsystem D consists of two identical controllers running in active parallel having the same rate of failure and repair. System failure with respect of subsystem D occurs whenever the entire controllers failed. With $n = 2$ and $k = 4$, the system of first order differential difference equation using Figure 2 are:

$$\frac{d}{dt}h_0(t) = -2\eta_4 h_0(t) + \delta_4 h_1(t) \tag{68}$$

$$\frac{d}{dt}h_1(t) = -(\eta_4 + \delta_4)h_1(t) + 2\eta_4 h_0(t) + \delta_4 h_2(t) \tag{69}$$

$$\frac{d}{dt}h_2(t) = -\delta_4 h_2(t) + \eta_4 h_1(t) \tag{70}$$

Solving (68) to (70) in steady state to obtain the following state probabilities

$$h_1(\infty) = 2\vartheta_4 h_0(\infty) \tag{71}$$

$$h_2(\infty) = 2\vartheta_4^2 h_0(\infty) \tag{72}$$

The normalising condition for this analysis is,

$$h_0(\infty) + h_1(\infty) + h_2(\infty) = 1 \tag{73}$$

Using (71)–(72) in (73) to obtain the initial probability below

$$h_0(\infty) = \frac{1}{\left(1 + 2\vartheta_4 + 2\vartheta_4^2\right)} \tag{74}$$

The availability of subsystem D is

$$A_{\vartheta 4}(\infty) = h_0(\infty) + h_1(\infty) \tag{75}$$

Substituting (71)–(72) and (74) in (75), the expression for the availability of subsystem D is

$$A_{\vartheta 4}(\infty) = \frac{1 + 2\vartheta_4}{1 + 2\vartheta_4 + 2\vartheta_4^2} \tag{76}$$

From equations (2)–(8), the reliability, maintainability, dependability ratio and dependability of subsystem D are

$$R_{\vartheta 4}(t) = e^{-\eta_4 t} \tag{77}$$

$$M_{\vartheta 4}(t) = 1 - e^{-\eta_4 t} \tag{78}$$

$$d = \frac{0.29}{0.0047} = 59 \tag{79}$$

$$D_{S4} = 1 - \left(\frac{1}{59-1}\right)\left(e^{-\frac{Ln59}{59-1}} - e^{-\frac{59\,Ln59}{59-1}}\right) = 0.984202 \tag{80}$$

5.6 RAMD formulation of subsystem E

Subsystem E consists of one switch. System failure with respect of subsystem E occurs whenever the switch failed. With $n = 2$ and $k = 5$, the system of first order differential difference equation using Figure 2 are:

$$\frac{d}{dt}h_0(t) = -\eta_5 h_0(t) + \delta_5 h_1(t) \tag{81}$$

$$\frac{d}{dt}h_1(t) = -\delta_5 h_1(t) + \eta_5 h_0(t) \tag{82}$$

Solving (81) to (82) in steady state to obtain the following state probabilities

$$h_1(\infty) = \vartheta_5 h_0(\infty) \tag{83}$$

The normalising condition for this analysis is,

$$h_0(\infty) + h_1(\infty) = 1 \tag{84}$$

Substituting (83) in (84) to give

$$h_0(\infty) = \frac{1}{(1+\vartheta_5)} \tag{85}$$

The availability of subsystem E is

$$A_{\vartheta 5} = h_0(\infty) = \frac{1}{1+\vartheta_5} \tag{86}$$

From equations (2)–(8), the reliability, maintainability, dependability ratio and dependability of subsystem E are

$$R_{\vartheta 5}(t) = e^{-\eta_5 t} \tag{87}$$

$$M_{\vartheta 5}(t) = 1 - e^{-\eta_5 t} \tag{88}$$

$$d = \frac{0.38}{0.0072} = 53 \tag{89}$$

$$D_{S5} = 1 - \left(\frac{1}{53-1}\right)\left(e^{-\frac{Ln53}{53-1}} - e^{-\frac{53\,Ln53}{53-1}}\right) = 0.982519 \tag{90}$$

5.7 RAMD formulation of subsystem F

Subsystem F consists of one supervisor controller. System failure with respect of subsystem F occurs whenever the supervisor controller failed. With $n = 1$ and $k = 6$, the system of first order differential difference equation using Figure 2 are:

$$\frac{d}{dt} h_0(t) = -\eta_6 h_0(t) + \delta_6 h_1(t) \tag{90}$$

$$\frac{d}{dt} h_2(t) = -\delta_6 h_2(t) + \eta_6 h_1(t) \tag{91}$$

Solving (90) to (91) in steady state to obtain the following state probabilities

$$h_1(\infty) = \vartheta_6 h_0(\infty) \tag{92}$$

With normalising condition

$$h_0(\infty) + h_1(\infty) = 1 \tag{93}$$

Substituting (92) in (93) to give

$$h_0(\infty) = \frac{1}{(1 + \vartheta_6)} \tag{94}$$

The expression of availability for subsystem F is

$$A_{\vartheta 6} = h_0(\infty) = \frac{1}{1 + \vartheta_6} \tag{95}$$

From equations (2)–(8), the reliability, maintainability, dependability ratio and dependability of subsystem F are

$$R_{\vartheta 6}(t) = e^{-\eta_6 t} \tag{96}$$

$$M_{\vartheta 6}(t) = 1 - e^{-\eta_6 t} \tag{97}$$

$$d = \frac{0.46}{0.0051} = 90 \tag{98}$$

$$D_{S6} = 1 - \left(\frac{1}{90 - 1}\right)\left(e^{-\frac{Ln 90}{90-1}} - e^{-\frac{90\, Ln 90}{90-1}}\right) = 0.989437 \tag{99}$$

6 Results and discussion

The following set of parameter values arbitrarily chosen are used in this section to compute RAMD of both subsystems and entire system: $\delta_1 = 0.025$, $\delta_2 = 0.005$, $\delta_3 = 0.0037$, $\delta_4 = 0.0049$, $\delta_5 = 0.0072$, $\delta_6 = 0.0051$, $\eta_1 = 1.2$, $\eta_2 = 0.82$, $\eta_3 = 0.78$, $\eta_4 = 0.29$, $\eta_5 = 1.38$ and $\eta_6 = 0.46$.

Since the system under study is series-parallel, maintainability availability, dependability and reliability, of the system are

$$R_{system} = \prod_{k=1}^{8} R_{\vartheta k}(t) \tag{100}$$

$$A_{\vartheta}(\infty) = \prod_{k=1}^{8} A_{\vartheta k} \tag{101}$$

$$M_{system}(t) = \prod_{k=1}^{8} M_{\vartheta k} = \prod_{k=1}^{8} \left(1 - e^{-\eta_k(t)}\right) \tag{102}$$

$$D_{System} = \prod_{k=1}^{8} D_{\vartheta k} \tag{103}$$

System dependability which is the product of the dependability of its constituent components is calculated below:

$$D_{System} = \prod_{k=1}^{6} D_{\vartheta k} = 0.928886$$

Table 2 System performance metrics

RAMD indices of subsystems	*Subsystem A*	*Subsystem B*	*Subsystem C*	*Subsystem D*
Reliability	$e^{-0.001t}$	$e^{-0.002t}$	$e^{-0.003t}$	$e^{-0.004t}$
Maintainability	$1 - e^{-9.6t}$	$1 - e^{-3.3t}$	$1 - e^{-1.6t}$	$1 - e^{-0.6t}$
Availability	0.896236	0.975760	0.996434	0.976473
MTBF	5.000	50.000	135.135	102.041
MTTR	0.1042	0.3049	0.6410	1.7241
Dependability	0.980814	0.994428	0.995380	0.984202
Dependability ratio	47.985	163.988	210.819	59.185
RAMD indices of subsystems	*Subsystem E*	*Subsystem F*	*System*	
Reliability	$e^{-0.01t}$	$e^{-0.004t}$	$e^{-0.01t}$	
Maintainability	$1 - e^{-0.4t}$	$1 - e^{-0.55t}$	$1 - e^{-5t}$	
Availability	0.986810	0.974636	0.818371	
MTBF	138.889	196.078	627.143	
MTTR	2.6316	2.1739	7.5797	
Dependability	0.982519	0.989437	0.928886	
Dependability ratio	52.777	90.196		

Table 3 shows that the reliability of the overall system for 20 days is 0.006806, while the probability of subsystems for time t = 20 days is $R_{s1}(t)$ = 0.018316, $R_{s2}(t)$ = 0.670320, $R_{s3}(t)$ = 0.862431, $R_{s4}(t)$ = 0.822012, $R_{s5}(t)$ = 0.865888, $R_{s6}(t)$ = 0.903030, respectively. As indicated in table 16, the chance of satisfactory maintenance and repair being completed within 20 days is 1.00000, and the related subsystems maintainability values are $M_{s1}(t)$ = 1.00000, $M_{s2}(t)$ = 1.00000, $M_{s3}(t)$ = 1.00000, $M_{s4}(t)$ = 0.99991, $M_{s5}(t)$ = 0.99949, and $M_{s6}(t)$ = 0.99989. In comparison to the reliability of other subsystems, subsystem 1's reliability is extremely low at any given time. As seen in Table 3, this has a significant impact on the overall system reliability. The sensitivity of subsystem 1 can also be evident in its availability and dependability which are low when compared with the availability and dependability of other subsystems. Table 1 depicts this. These analyses suggest that subsystem 1 is the most vulnerable (sensitive) which necessitates a great deal of attention and strict maintenance policies.

The variance in system reliability due to subsystem failure rates is shown in Tables 5, 6, 7, 8, and 9. We can see from these tables that subsystem 1 is quite sensitive to failure rate. These tables also show that subsystem 2, which has the lowest failure rates among the six subsystems, provides the most system reliability. This analysis can be used to defend the fact that optimal system reliability and dependability can be attained when the total system failure rate is low.

Table 3 Reliability of the individual subsystems against time

Time (in days)	$R_{s1}(t)$	$R_{s2}(t)$	$R_{s3}(t)$	$R_{s4}(t)$	$R_{s5}(t)$	$R_{s6}(t)$	$R_{sys}(t)$
0	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
10	0.135335	0.818731	0.928672	0.906649	0.930531	0.950278	0.082496
20	0.018316	0.670320	0.862431	0.822012	0.865888	0.903030	0.006806
30	0.002479	0.548812	0.800915	0.745276	0.805735	0.858130	0.000561
40	0.000335	0.449329	0.743787	0.675704	0.749762	0.815462	0.000046
50	0.000045	0.367879	0.690734	0.612626	0.697676	0.774916	0.000004
60	0.000006	0.301194	0.641465	0.555437	0.649209	0.736387	0.000001
70	0.000001	0.246597	0.595711	0.503586	0.604109	0.699772	0.000000
80	0.000000	0.201897	0.553220	0.456576	0.562142	0.664979	0.000000
90	0.000000	0.165299	0.513760	0.413954	0.523091	0.631915	0.000000
100	0.000000	0.135335	0.477114	0.375311	0.486752	0.600496	0.000000

Table 4 Reliability of the system and subsystem A against time for different values of

Time (in days)	*System*		*Subsystem A*	
	$\delta_1 = 0.003$	$\delta_1 = 0.004$	$\delta_1 = 0.003$	$\delta_1 = 0.004$
0	1.000000	1.000000	1.000000	1.000000
10	0.591555	0.585669	0.970446	0.960789
20	0.349938	0.343009	0.941765	0.923116
30	0.207008	0.200890	0.913931	0.886920
40	0.122456	0.117655	0.886920	0.852144
50	0.072440	0.068907	0.860708	0.818731
60	0.042852	0.040357	0.835270	0.786628
70	0.025349	0.023636	0.810584	0.755784
80	0.014996	0.013843	0.786628	0.726149
90	0.008871	0.008108	0.763379	0.697676
100	0.005248	0.004748	0.740818	0.670320

Table 5 Variation in reliability of system due to variation in failure rate of subsystem B

Time (in days)	*System*		*Subsystem 2*	
	$\delta_2 = 0.001$	$\delta_2 = 0.002$	$\delta_2 = 0.001$	$\delta_2 = 0.002$
0	1.000000	1.000000	1.000000	1.000000
10	0.099759	0.098766	0.990050	0.980199
20	0.009952	0.009755	0.980199	0.960789
30	0.000993	0.000963	0.970446	0.941765
40	0.000099	0.000095	0.960789	0.923116
50	0.000012	0.000011	0.951229	0.904837
60	0.000010	0.000001	0.941765	0.886920
70	0.000001	0.000000	0.932394	0.869358
80	0.000000	0.000000	0.923116	0.852144
90	0.000000	0.000000	0.913931	0.835270
100	0.000000	0.000000	0.904837	0.818731

Table 6 Variation in reliability of system due to variation in failure rate of subsystem C

Time (in days)	*System*		*Subsystem 3*	
	$\delta_3 = 0.006$	$\delta_3 = 0.007$	$\delta_3 = 0.006$	$\delta_3 = 0.007$
0	1.000000	1.000000	1.000000	1.000000
10	0.083660	0.082827	0.941765	0.932394
20	0.006999	0.006860	0.886920	0.869358
30	0.000586	0.000568	0.835270	0.810584
40	0.000049	0.000047	0.786628	0.755784
50	0.0000041	0.000004	0.740818	0.704688
60	0.0000030	0.000001	0.697676	0.657047
70	0.0000004	0.000000	0.657047	0.612626
80	0.0000001	0.000000	0.618783	0.571209
90	0.0000000	0.000000	0.582748	0.532592
100	0.0000000	0.000000	0.548812	0.496585

Table 7 Variation in reliability of system due to variation in failure rate of subsystem D

Time (in days)	*System*		*Subsystem 4*	
	$\delta_4 = 0.0075$	$\delta_4 = 0.0085$	$\delta_4 = 0.0075$	$\delta_4 = 0.0085$
0	1.000000	1.000000	1.000000	1.000000
10	0.084416	0.083576	0.927743	0.918512
20	0.007126	0.006985	0.860708	0.843665
30	0.000602	0.000584	0.798516	0.774916
40	0.000051	0.000049	0.740818	0.711770
50	0.000004	0.000004	0.687289	0.653770
60	0.000001	0.000000	0.637628	0.600496
70	0.000000	0.000000	0.591555	0.551563
80	0.000000	0.000000	0.548812	0.506617
90	0.000000	0.000000	0.509156	0.465334
100	0.000000	0.000000	0.472366	0.427415

Table 8 Variation in reliability of system due to variation in failure rate of subsystem E

Time (in days)	*System*		*Subsystem 5*	
	δ_5 = 0.009	*δ_5 = 0.0010*	*δ_5 = 0.009*	*δ_5 = 0.010*
0	1.000000	1.000000	1.000000	1.000000
10	0.081025	0.080219	0.913931	0.904837
20	0.006565	0.006435	0.835270	0.818731
30	0.000532	0.000516	0.763379	0.740818
40	0.000043	0.000041	0.697676	0.670320
50	0.000003	0.000003	0.637628	0.606531
60	0.000000	0.000000	0.582748	0.548812
70	0.000000	0.000000	0.532592	0.496585
80	0.000000	0.000000	0.486752	0.449329
90	0.000000	0.000000	0.444858	0.406570
100	0.000000	0.000000	0.406570	0.367879

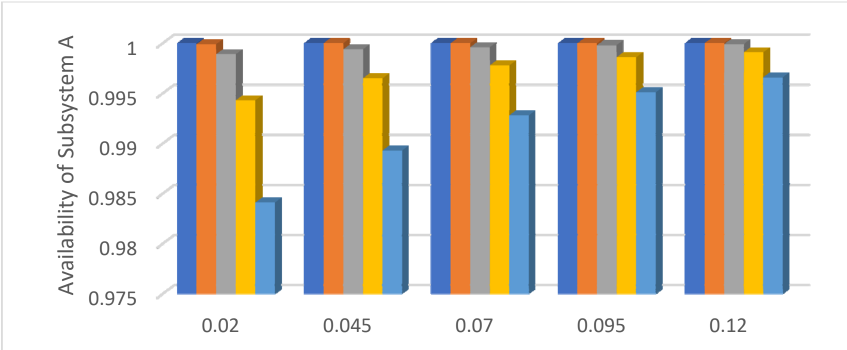
Table 9 Variation in reliability of system due to variation in failure rate of subsystem F

Time (in days)	*System*		*Subsystem 6*	
	δ_6 = 0.017	*δ_5 = 0.027*	*δ_5 = 0.017*	*δ_5 = 0.027*
0	1.000000	1.000000	1.000000	1.000000
10	0.073241	0.066271	0.843665	0.763379
20	0.005364	0.004392	0.711770	0.582748
30	0.000393	0.000291	0.600496	0.444858
40	0.000029	0.000019	0.506617	0.339596
50	0.000002	0.000001	0.427415	0.259240
60	0.000000	0.000000	0.360595	0.197899
70	0.000000	0.000000	0.304221	0.151072
80	0.000000	0.000000	0.256661	0.115325
90	0.000000	0.000000	0.216536	0.088037
100	0.000000	0.000000	0.182684	0.067206

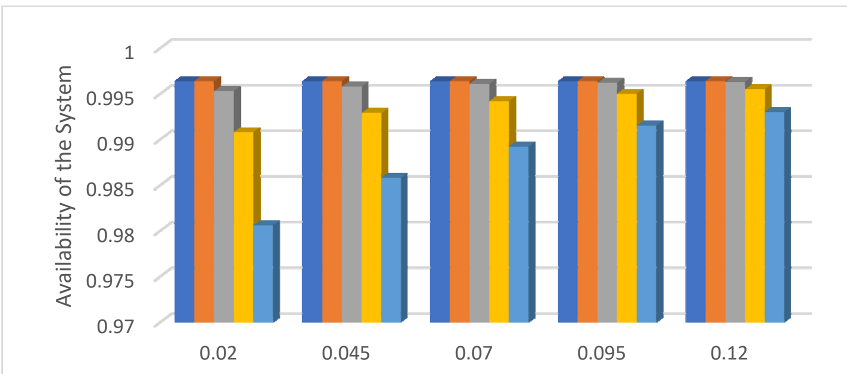
Table 10 Variation in availability due to variation in failure and repair rate of subsystem A

η_1	*Availability of subsystem A*					*Availability of the system*				
	δ_1					δ_1				
	0.50	*0.55*	*0.60*	*0.65*	*0.7*	*0.50*	*0.55*	*0.60*	*0.65*	*0.7*
0.02	1.0000	1.0000	1.0000	1.0000	1.0000	0.9964	0.9964	0.9964	0.9964	0.9964
0.045	0.9999	1.0000	1.0000	1.0000	1.0000	0.9964	0.9964	0.9964	0.9964	0.9964
0.07	0.9989	0.9994	0.9996	0.9998	0.9999	0.9953	0.9958	0.9961	0.9962	0.9963
0.095	0.9943	0.9965	0.9978	0.9986	0.9991	0.9908	0.9929	0.9942	0.9950	0.9955
0.12	0.9841	0.9893	0.9928	0.9951	0.9966	0.9806	0.9858	0.9892	0.9915	0.9930

Figure 3 (a) Availability of subsystem A against η_1 (b) Availability of the system against η_1 (see online version for colours)



(a)

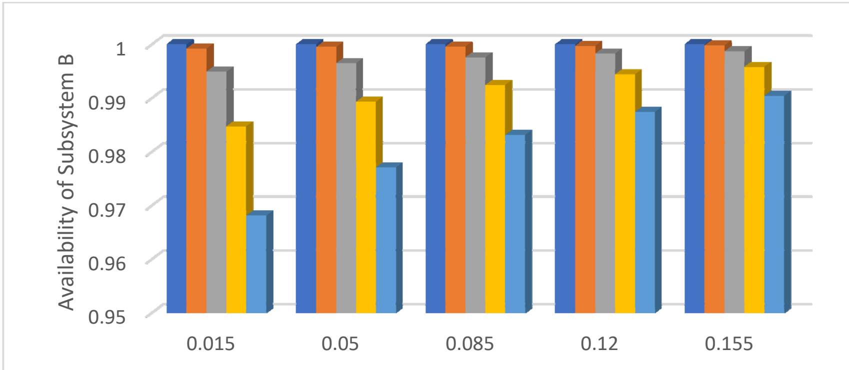


(b)

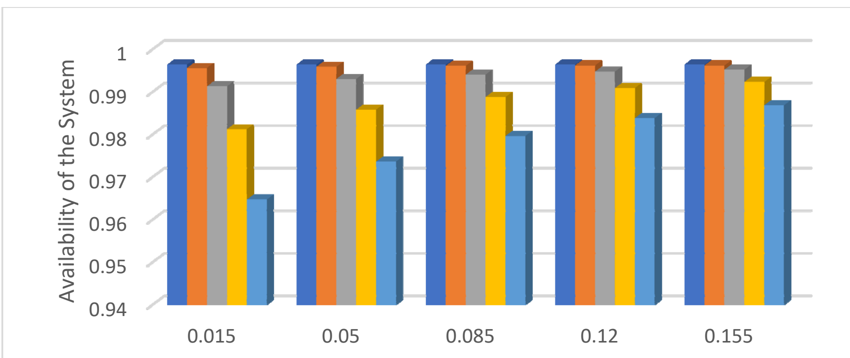
Table 11 Variation in availability due to variation in failure and repair rate of subsystem B

η_2	*Availability of subsystem B*					*Availability of the system*				
	δ_2					δ_2				
	0.6	*0.675*	*0.75*	*0.825*	*0.9*	*0.6*	*0.675*	*0.75*	*0.825*	*0.9*
0.015	1.0000	1.0000	1.0000	1.0000	1.0000	0.9964	0.9964	0.9964	0.9964	0.9964
0.05	0.9992	0.9995	0.9996	0.9997	0.9998	0.9956	0.9959	0.9961	0.9962	0.9962
0.085	0.9949	0.9965	0.9976	0.9983	0.9987	0.9913	0.9930	0.9940	0.9947	0.9952
0.12	0.9847	0.9893	0.9924	0.9944	0.9958	0.9812	0.9858	0.9888	0.9909	0.9923
0.155	0.9681	0.9771	0.9831	0.9874	0.9904	0.9647	0.9736	0.9796	0.9838	0.9868

Figure 4 (a) Availability of subsystem B against η_2 (b) Availability of the system B against is η_2 (see online version for colours)



(a)

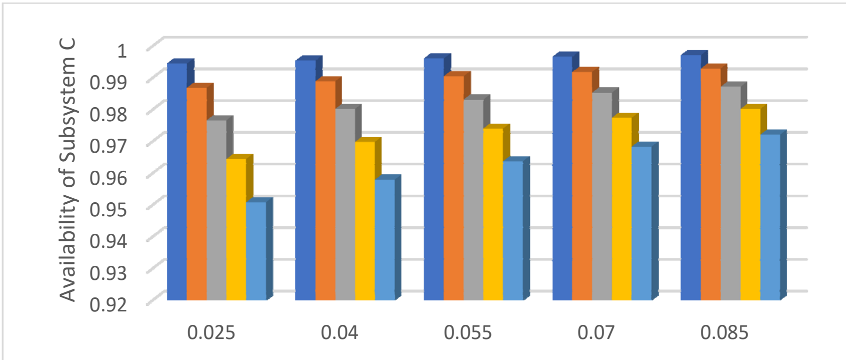


(b)

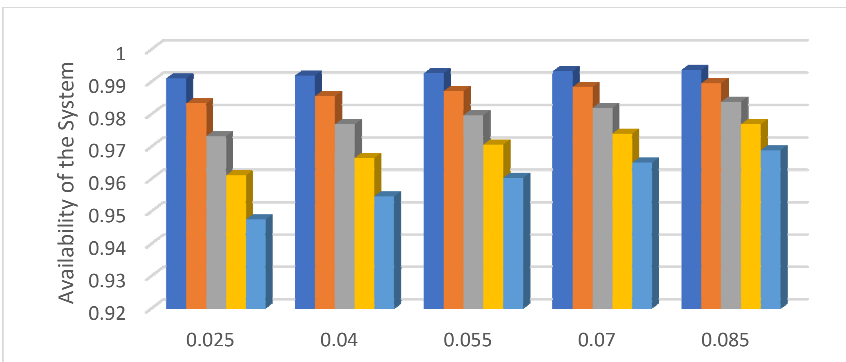
Table 12 Variation in availability due to variation in failure and repair rate of subsystem C

η_3	*Availability of subsystem C*					*Availability of the system*				
	δ_3					δ_3				
	0.45	*0.495*	*0.54*	*0.585*	*0.63*	*0.45*	*0.495*	*0.54*	*0.585*	*0.63*
0.025	0.9945	0.9954	0.9961	0.9966	0.9971	0.9909	0.9918	0.9925	0.9931	0.9935
0.04	0.9868	0.9889	0.9905	0.9918	0.9929	0.9832	0.9854	0.9870	0.9883	0.9894
0.055	0.9766	0.9802	0.9831	0.9853	0.9872	0.9731	0.9767	0.9795	0.9818	0.9837
0.07	0.9644	0.9698	0.9740	0.9774	0.9802	0.9610	0.9663	0.9705	0.9739	0.9767
0.085	0.9508	0.9579	0.9637	0.9683	0.9721	0.9474	0.9545	0.9602	0.9649	0.9687

Figure 5 (a) Availability of subsystem C against η_3 (b) Availability of the system against η_3 (see online version for colours)



(a)

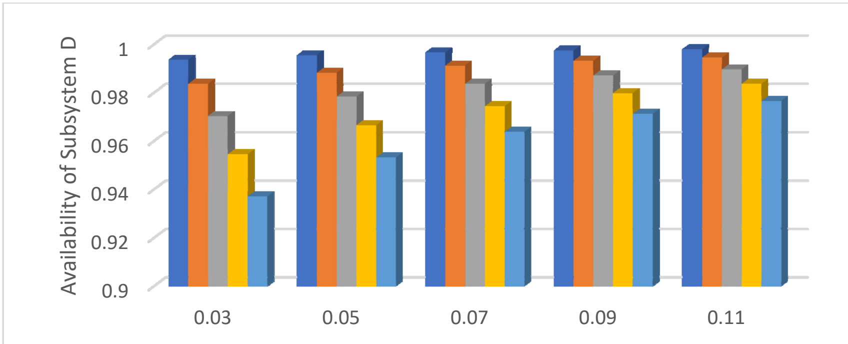


(b)

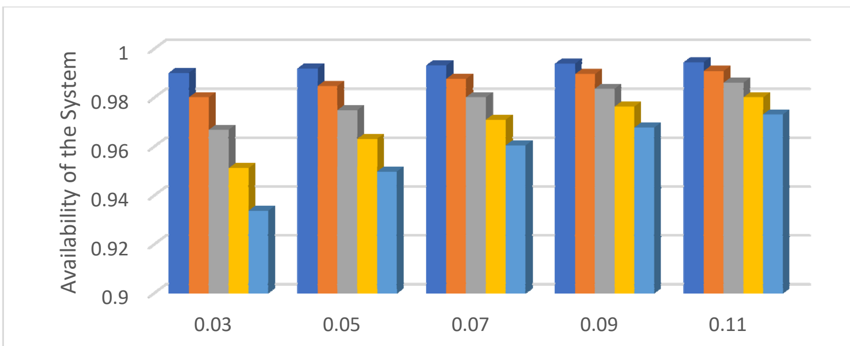
Table 13 Variation in availability due to variation in failure and repair rate of subsystem D

η_4	*Availability of subsystem D*					*Availability of the system*				
	δ_4					δ_4				
	0.5	*0.6*	*0.7*	*0.8*	*0.9*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*
0.03	0.9936	0.9955	0.9966	0.9974	0.9979	0.9901	0.9919	0.9931	0.9938	0.9944
0.05	0.9836	0.9882	0.9912	0.9931	0.9945	0.9801	0.9847	0.9876	0.9896	0.9909
0.07	0.9703	0.9784	0.9836	0.9871	0.9896	0.9668	0.9749	0.9801	0.9836	0.9861
0.09	0.9545	0.9665	0.9744	0.9798	0.9836	0.9511	0.9631	0.9709	0.9763	0.9801
0.11	0.9370	0.9531	0.9638	0.9712	0.9766	0.9337	0.9497	0.9604	0.9677	0.9731

Figure 6 (a) Availability of subsystem D against η_4 (b) Availability of the system against η_4 (see online version for colours)



(a)

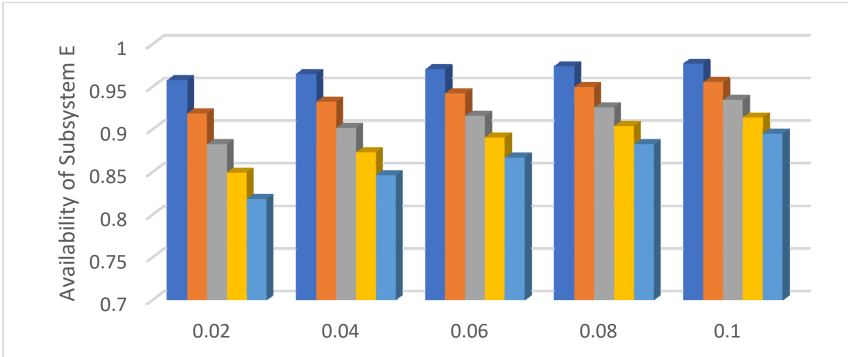


(b)

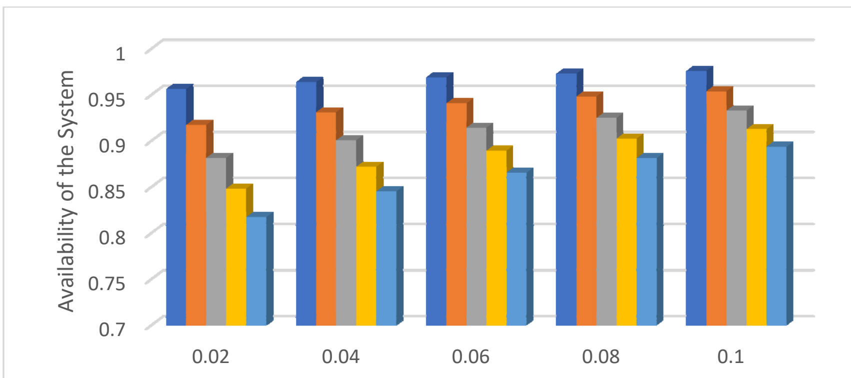
Table 14 Variation in availability due to variation in failure and repair rate of subsystem E

η_5	*Availability of subsystem E*					*Availability of the system*				
	δ_5					δ_5				
	0.45	*0.55*	*0.65*	*0.75*	*0.85*	*0.45*	*0.55*	*0.65*	*0.75*	*0.85*
0.02	0.9574	0.9649	0.9701	0.9740	0.9770	0.9561	0.9636	0.9688	0.9727	0.9757
0.04	0.9184	0.9322	0.9420	0.9494	0.9551	0.9171	0.9309	0.9407	0.9481	0.9538
0.06	0.8824	0.9016	0.9155	0.9259	0.9341	0.8812	0.9004	0.9142	0.9247	0.9328
0.08	0.8491	0.8730	0.8904	0.9036	0.9140	0.8479	0.8718	0.8892	0.9024	0.9127
0.1	0.8182	0.8462	0.8667	0.8824	0.8947	0.8171	0.8450	0.8655	0.8812	0.8935

Figure 7 (a) Availability of subsystem E against η_5 (b) Availability of the system against η_5 (see online version for colours)



(a)

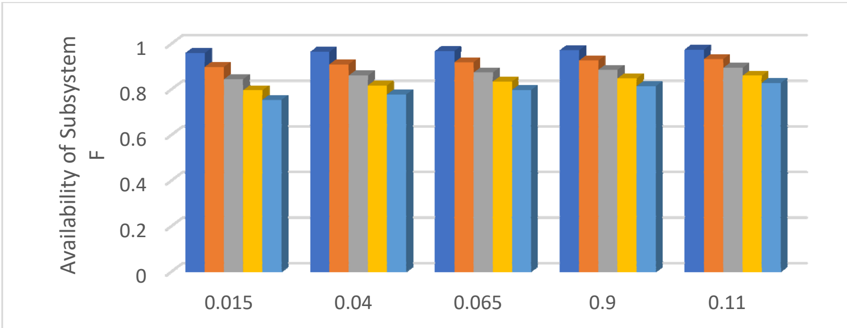


(b)

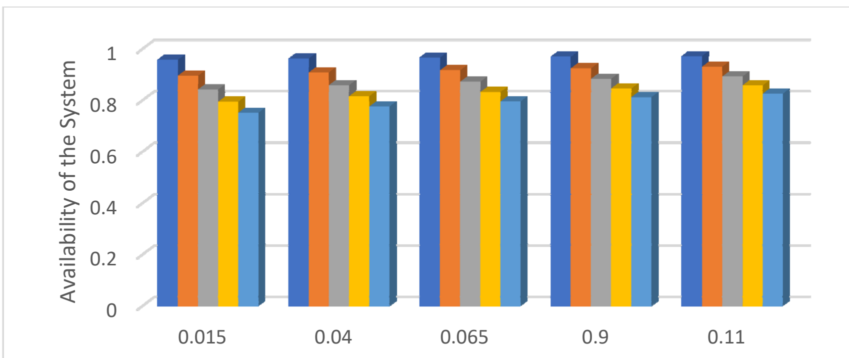
Table 15 Variation in availability due to variation in failure and repair rate of subsystem F

η_6	*Availability of subsystem F*					*Availability of the system*				
	δ_6					δ_6				
	0.35	*0.4*	*0.45*	*0.5*	*0.55*	*0.35*	*0.4*	*0.45*	*0.5*	*0.55*
0.015	0.9589	0.9639	0.9677	0.9709	0.9735	0.9568	0.9617	0.9656	0.9687	0.9713
0.04	0.8974	0.9091	0.9184	0.9259	0.9322	0.8954	0.9071	0.9163	0.9238	0.9301
0.065	0.8434	0.8602	0.8738	0.8850	0.8943	0.8415	0.8583	0.8718	0.8830	0.8923
0.09	0.7955	0.8163	0.8333	0.8475	0.8594	0.7937	0.8145	0.8315	0.8456	0.8574
0.115	0.7527	0.7767	0.7965	0.8130	0.8271	0.7510	0.7750	0.7947	0.8112	0.8252

Figure 8 (a) Availability of subsystem F against η_6 (b) Availability of the system against η_6 (see online version for colours)



(a)



(b)

Table 16 Variation of maintainability of subsystems with respect to time

Time (in months)	$M_{s1}(t)$	$M_{s2}(t)$	$M_{s3}(t)$	$M_{s4}(t)$	$M_{s5}(t)$	$M_{s6}(t)$	$M_{sys}(t)$
0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
10	1.00000	1.00000	0.99999	0.996972	0.97763	0.98995	1.00000
20	1.00000	1.00000	1.00000	0.999991	0.99949	0.99989	1.00000
30	1.00000	1.00000	1.00000	0.999999	0.99998	0.99999	1.00000
40	1.00000	1.00000	1.00000	0.999990	0.99999	0.99999	1.00000
50	1.00000	1.00000	1.00000	1.00000	0.99999	0.99999	1.00000
60	1.00000	1.00000	1.00000	1.00000	0.99999	1.00000	1.00000
70	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
80	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
90	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
100	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

Tables 10–15 and Figures 3(a), 3(b), 4(a), 4(b), 5(a), 5(b), 6(a), 6(b), 7(a), 7(b), 8(a), and 8(b) depict the impact of repair and failure rates of each subsystem on the availability of each subsystem and overall subsystem. As seen in these tables and their associated figures, the availability of each subsystem and overall system availability improves as the values of repair rates grow, while they decrease as the values of failure rates of each subsystem increase. These tables and figures show that the failure and repair rates of subsystem 1 have a greater impact on total system availability. This analysis takes a lot of focus and adherence to stringent maintenance guidelines to this subsystem (subsystem 1).

7 Conclusions

Many computer network systems are made up of numerous components or subsystems, and their smooth operation is determined by the performance of their important components or subsystems. For this reason, it is critical to first identify the most sensitive component(s)/subsystem(s), and then implement some maintenance practices to enhance the system's performance of that sensitive component(s)/subsystem(s). Thus, the RAMD indices for each subsystem are studied in this paper to determine which of the subsystem is the most sensitive of the system under review. All subsystem transition diagrams are formulated, as well as Chapman-Kolmogorov differential equations. Numerical values on RAMD, all of which are important in RAMD analysis, have been obtained and are given in tables and graphs. Other metrics have been acquired, including MTTF, MTBF, dependability ratio, and dependability minimum. Based on the numerical values and the behavior of the graphs, subsystem 1 has been discovered to have the lowest availability and reliability. Thus, it is necessary to begin improving the system's performance from this subsystem/component. It's also worth noting that subsystem 1 has the lowest level of dependability. The lesser the amount of dependability, the more unpredictable the operation of the system becomes, the better the upkeep. If the findings of this study are modified, system engineers and maintenance managers will be able to avoid making incorrect reliability assessments. The future research direction will analyse coverage factor, Lindley distribution, exponentiated Weibull distribution, application of metaheuristics, such as genetic algorithm, hybrid genetic algorithm, Gray-Wolf optimisation, and particle swarm optimisation in the study.

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