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A Comparative Study of Hybrid Systems Using Reliability, Availability, Maintainability, and Dependability Analysis

Abdullahi Sanusi[1], Ibrahim Yusuf[2], Zulyadaini Dahiru Lawan[1*]

[1] School of Continuing Education (SCE), Bayero University, Kano, Nigeria; asanusi.sce@buk.edu.ng; zdlawan.sce@buk.edu.ng.
[2] Department of Mathematical Science, Bayero University, Kano, Nigeria; iyusuf.mth@buk.edu.ng.

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Abstract

Hybrid systems, combining diverse technologies or methodologies, have emerged as promising solutions across various domains, from renewable energy to transportation and beyond. This study conducts a comprehensive analysis of hybrid systems employing the Reliability, Availability, Maintainability, and Dependability (RAMD) framework. In this study, two systems are established, each composed of subsystems A and B. In the first system, both A and B contain active units, with two units in A and four in B. In the second system, A has two active units, while B is split between two human operators: 1) one overseeing two units, and 2) the other managing four. The objective is to evaluate and compare their performance, considering their RAMD aspects. RAMD analysis plays a pivotal role in optimizing operational efficiency and productivity by identifying opportunities for improvement within systems.

Keywords: Availability, Analysis, Comparative, Dependability, Hybrid, Maintainability, Reliability.

1 | Introduction

In the ever-evolving landscape of engineering and technology, the integration of hybrid systems has emerged as a promising solution across various industries. Hybrid systems, blending different technologies or methodologies, offer versatile advantages, ranging from enhanced performance to increased resilience. Amidst this surge in hybridization, the utilization of Reliability, Availability, Maintainability, and Dependability (RAMD) analysis stands out as a fundamental approach in assessing and optimizing these complex systems. This comparative investigation explores the domain/field of hybrid systems, employing RAMD analysis as a cornerstone for evaluation. By comparing different hybrid setups, this study aims to

Corresponding Author: zdlawan.sce@buk.edu.ng

unravel insights into their RAMD aspects, thus shedding light on their operational effectiveness and potential areas for enhancement.

To gain valuable insights for this study, we have thoroughly examined relevant literature, including various related works. These include; Dahiya et al. [1] applied RAMD methodology to assess the effectiveness and efficiency of the A-Pan crystallization system in the sugar industry. Similarly, Saini and Kumar [2] utilized RAMD analysis to thoroughly examine the operational performance of a sugar sector evaporation system. Choudhary et al. [3] proposed a methodology aimed at improving the reliability of cement plants, conducting a two-year analysis of Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR), along with a comprehensive RAMD index analysis.

Velmurugan et al. [4] investigated Reliability, Availability, Maintainability (RAM) in the forming industry, while Goyal et al. [5] focused on RAMD aspects of a Sewage Treatment Plant's (STEPs) physical processing unit, utilizing Markovian processes and Chapman-Kolmogorov equations. Kumar et al. [6] delved into the reliability and maintainability of a STEP's power-producing unit, while Sanusi and Ibrahim [7] analyzed RAMD in a computer-based test network system. Jagtap et al. [8] innovatively utilized Markov models to estimate RAM performance in water circulation systems, while Gupta et al. [9] investigated generator reliability in STEPs using a RAMD approach at the component level. Jakkula et al. [10] conducted a thorough examination of Random-Access Memory (RAM) in Load Haul Dumpers (LHDs), and Danjuma et al. [11] utilized the Markov birth-death process to assess RAMD in a series-parallel system. Additionally, Kumar et al. [12] conducted a comprehensive RAMD investigation focusing on Tube-wells Integrated with Underground Pipelines (TIUP) for irrigation systems. Their study incorporated RAMD and Failure Modes and Effects Analysis (FMEA), using a novel stochastic model with the Markovian approach to determine Steady-State Availability (SSA) of the TIUP, offering valuable insights into its performance under various conditions.

Following an in-depth review of the existing literature, this study undertakes a comparative assessment of two hybrid systems' performance utilizing RAMD, with the objective of identifying opportunities to enhance efficiency.

1.1 | Notations

t : time scale.

D_{min} : dependability minimum.

γ_1 : the rate at which any unit within subsystem A experiences failure.

κ_1 : the rate at which any unit within subsystem A undergoes repair.

γ_2 : the rate at which any unit within subsystem B experiences failure.

κ_2 : the rate at which any unit within subsystem B undergoes repair.

H_1 : the failure rate attributed to human operator 1.

H_2 : the failure rate attributed to human operator 2.

1.2 | Description of the Systems

This study examines two analogous systems, each consisting of two subsystems, A and B. In both systems, subsystem A incorporates two active units, while subsystem B comprises four units. However, a notable distinction lies in the operational dynamics of the second system: Subsystem A is manned by human operator 1, whereas subsystem B is under the supervision of human operator 2. In both systems under consideration, the failure and repair rates remain consistent over time. Whenever a unit experiences a failure within each subsystem of both systems, it is dispatched for repairs without delay. This immediate response ensures minimal downtime and facilitates swift restoration of functionality to maintain operational efficiency. In the initial system configuration, as specified, the operational integrity relies on the presence of two units from subsystem A and three units from subsystem B. In this system, unit failures within each subsystem are considered inherent and inevitable, reflecting the system's dynamic nature. The operational reliability of both subsystems within the first system mirrors that of the second system's subsystems. However, in the second system, unit failures within each subsystem are inherently natural and due to human error attributed to the actions of their respective operators.

2 | Methodology

In this section, we have used Chapman-Kolmogorov differential equations to model each subsystem in both systems, using the Markov birth-death process. This modeling approach helps us deeply understand how the systems behave over time. Transition tables (*Tables 1-4*) outline state changes in each subsystem, aiding in identifying operational patterns and potential issues. Additionally, we have used the Chapman-Kolmogorov equations to assess important system performance metrics like availability, reliability, maintainability, and dependability. Solving these equations under steady-state conditions and applying normalization provides understanding of the system's overall performance and resilience across various operational scenarios.

2.1 | Evaluation of the First System Configuration

Subsystem A Analysis

Table 1. Transition table of subsystem A of the first model.

States	Status	S_0	S_1	S_2
S_0	Perfect state	0	$2\gamma_1$	0
S_1	Partial failure state	κ_1	0	γ_1
S_2	Complete failure state	0	κ_1	0

Table 1 above provides an overview of the state transitions within subsystem A of the first system. These transitions form the basis for deriving the following differential equations:

$$\frac{d}{dt}\left(q_0(t)\right) = -2\gamma_1 q_0 + \kappa_1 q_1. \quad (1)$$

$$\frac{d}{dt}\left(q_1(t)\right) = 2\gamma_1 q_0 - \left(\gamma_1 + \kappa_1\right) q_1 + \kappa_1 q_2. \quad (2)$$

$$\frac{d}{dt}\left(q_3(t)\right) = \gamma_1 q_1 - \kappa_1 q_2. \quad (3)$$

At a steady-state condition, which denotes a state of equilibrium or stability within the system, we obtain the following:

$$-2\gamma_1 q_0 + \kappa_1 q_1 = 0. \quad (4)$$

$$2\gamma_1 q_0 - \left(\gamma_1 + \kappa_1\right) q_1 + \kappa_1 q_2 = 0. \quad (5)$$

$$\gamma_1 q_1 - \kappa_1 q_2 = 0. \quad (6)$$

By iteratively solving *Eqs. (4)-(6)* and using the normalization condition represented as $q_0 + q_1 + q_2 = 1$, we derive the subsequent results; $q_0 = \frac{1}{1+2y_1+2y_1^2}, q_1 = \frac{2y_1}{1+2y_1+2y_1^2}$, and $q_2 = \frac{2y_1^2}{1+2y_1+2y_1^2}$, where $y_1 = \frac{\gamma_1}{\kappa_1}$.

Now, to determine the SSA, we calculate it by summing up all probabilities associated with operational states, represented as

$$Av._{subsystem-A} = \frac{1+2y_1}{1+2y_1+2y_1^2}. \quad (7)$$

In general,

$$Av._{subsystem-A} = \frac{1+ny_1}{1+ny_1+ny_1^n}, n=2. \quad (8)$$

In contrast to previous studies utilizing exponential distribution for RAMD analysis assessment, we opt for another distribution in our evaluation of reliability. Thus, the measure of reliability for subsystem A is articulated as

$$R(t)=1-\left(1-e^{-(\gamma_1 t)^{0.2}}\right)^2. \quad (9)$$

The maintainability assessment for subsystem A is presented as follows:

$$M(t)=1-e^{-(\gamma_1 t)}. \quad (10)$$

These following formulas are essential for calculating different aspects of system reliability, including its overall dependability, minimum reliability threshold, key metrics like MTBF and MTTR.

$$\text{Dependability}(d)=\frac{MTBF}{MTTR}. \quad (11)$$

$$\text{Dependability minimum } (D_{min})=1-\left(\frac{1}{d-1}\right)\left(e^{-\ln d/d-1}-e^{-d\ln d/d-1}\right). \quad (12)$$

$$MTBF=\frac{1}{\text{Failure rate}}. \quad (13)$$

$$MTTTR=\frac{1}{\text{Repair rate}}. \quad (14)$$

We obtain the dependability, dependability minimum, MTBF, and MTTR of subsystem B using *Eqs. (11)-(14)* presented above as $MTBF=500hrs, MTTR=3hrs, d=167$ and $D_{min}=0.9942$.

Subsystem B Analysis

Table 2. Transition table of subsystem B of the first model.

States	Status	S_0	S_1	S_2	S_3
S_0	Perfect state	0	$3\gamma_2$	0	0
S_1	Partial failure state	κ_2	0	$2\gamma_2$	0
S_2	Partial failure state	0	κ_2	0	γ_2
S_3	Complete failure state	0	0	κ_2	0

We obtain the following differential equations from *Table 1* and are presented as

$$\frac{d}{dt}\left(q_0(t)\right)=-3\gamma_2 q_0+\kappa_2 q_1. \quad (15)$$

$$\frac{d}{dt}\left(q_1(t)\right)=3\gamma_2 q_0-\left(2\gamma_2+\kappa_2\right)q_1+\kappa_2 q_2. \quad (16)$$

$$\frac{d}{dt}\left(q_2(t)\right)=2\gamma_2 q_1-\left(\gamma_2+\kappa_2\right)q_2+\kappa_2 q_3. \tag{17}$$

$$\frac{d}{dt}\left(q_3(t)\right)=\gamma_2 q_2-\kappa_2 q_3. \tag{18}$$

At a steady-state, *Eqs. (15)* to *(16)* reduce to

$$-3\gamma_2 q_0+\kappa_2 q_1=0. \tag{19}$$

$$3\gamma_2 q_0-\left(2\gamma_2+\kappa_2\right)q_1+\kappa_2 q_2=0. \tag{20}$$

$$2\gamma_2 q_1-\left(\gamma_2+\kappa_2\right)q_2+\kappa_2 q_3=0. \tag{21}$$

$$\gamma_2 q_2-\kappa_2 q_3=0. \tag{22}$$

By solving *Eqs. (19)-(22)* and integrating the normalizing condition, we derive the following:

$q_0=\frac{1}{1+3y_2+6y_2^2+6y_2^3}, q_1=\frac{3y_2}{1+3y_2+6y_2^2+6y_2^3}, q_2=\frac{6y_2^2}{1+3y_2+6y_2^2+6y_2^3}$, and $q_3=\frac{6y_2^3}{1+3y_2+6y_2^2+6y_2^3}$, where $y_2=\frac{\gamma_2}{\kappa_2}$.

Thus, we can now articulate the SSA for subsystem B as

$$Av._{subsystem-B}=\frac{1+3y_2+6y_2^2}{1+3y_2+6y_2^2+6y_2^3}. \tag{23}$$

Eq. (24) is derived from *Eq. (23)* to specifically address subsystem B. This allows for the extension of its units when desired.

$$Av._{subsystem-B}=\frac{1+ny_2+n(n-1)y_2^2+n(n-1)(n-2)y_2^3+...+n!y_2^{n-1}}{1+ny_2+n(n-1)y_2^2+n(n-1)(n-2)y_2^3+...+n!y_2^{n-1}+n!y_2^n}. \tag{24}$$

Eq. (25) presents the reliability of subsystem B.

$$R(t)=1-\left(1-e^{-(\gamma_2 t)^{0.2}}\right)^2. \tag{25}$$

The maintainability of subsystem B is given by

$$M(t)=1-\exp^{-(\gamma_2 t)}. \tag{26}$$

We obtain the dependability, dependability minimum, MTBF, and MTTR of subsystem B using *Eqs. (11)-(14)* presented above as $MTBF=667hrs, MTTR=3hrs, d=222$ and $D_{min}=0.9956$.

2.2 | Evaluation of the Second System Configuration

This second subsystem is an extension of the initial model (system) by assigning subsystem A to human operator 1 and subsystem B to human operator B.

Subsystem A Analysis

Table 3. Transition table of subsystem A of the second model.

States	Status	S_0	S_1	S_2
S_0	Perfect state	0	$2\gamma_1 + H_1$	0
S_1	Partial failure state	κ_1	0	$\gamma_1 + H_1$
S_2	Complete failure state	0	κ_1	0

The following differential equations are derived from *Table 3* providing a mathematical model that describes how this subsystem behaves.

$$\frac{d}{dt}\left(q_0\left(t\right)\right) = -\left(2\gamma_1 + H_1\right)q_0 + \kappa_1 q_1. \tag{27}$$

$$\frac{d}{dt}\left(q_1\left(t\right)\right) = \left(2\gamma_1 + H_1\right)q_0 - \left(\gamma_1 + H_1 + \kappa_1\right)q_1 + \kappa_1 q_2. \tag{28}$$

$$\frac{d}{dt}\left(q_2\left(t\right)\right) = \left(\gamma_1 + H_1\right)q_1 - \kappa_1 q_2. \tag{29}$$

At steady-state, *Eqs. (27)-(29)* can be reduced to the following:

$$-\left(2\gamma_1 + H_1\right)q_0 + \kappa_1 q_1 = 0. \tag{30}$$

$$\left(2\gamma_1 + H_1\right)q_0 - \left(\gamma_1 + H_1 + \kappa_1\right)q_1 + \kappa_1 q_2 = 0. \tag{31}$$

$$\left(\gamma_1 + H_1\right)q_1 - \kappa_1 q_2 = 0. \tag{32}$$

By recursively solving *Eqs. (30)-(32)* and incorporating the normalization condition, expressed as $q_0 + q_1 + q_2 = 1$, we derive the following outcome:

$$q_0 = \frac{\kappa_1}{\kappa_1 + \left(2\gamma_1 + H_1\right)\left(1 + \gamma_1 + H_1\right)}, q_1 = \frac{\left(2\gamma_1 + H_1\right)}{\kappa_1 + \left(2\gamma_1 + H_1\right)\left(1 + \kappa_1 + H_1\right)}, q_2 = \frac{\left(\gamma_1 + H_1\right)\left(2\gamma_1 + H_1\right)}{\kappa_1\left[\kappa_1 + \left(2\kappa_1 + H_1\right)\left(1 + \kappa_1 + H_1\right)\right]}.$$

Now, to ascertain the SSA, we calculate it as the sum of all probabilities corresponding to operational states, which can be expressed as

$$Av._{subsystem-A} = q_0 + q_1 = \frac{2\gamma_1 + H_1 + \kappa_1}{\kappa_1 + \left(2\gamma_1 + H_1\right)\left(1 + \gamma_1 + H_1\right)}. \tag{33}$$

Eq. (34) is derived form *Eq. (33)*, specifically when $n = 2$.

$$Av._{subsystem-A} = \frac{n\gamma_1 + H_1 + \kappa_1}{\kappa_1 + \left(n\gamma_1 + H_1\right)\left(1 + \gamma_1 + H_1\right)}, n = 2. \tag{34}$$

The reliability of subsystem A of the second model is given as

$$R\left(t\right) = 1 - \left(1 - e^{-\left(\left(\gamma_1 + H_1\right)t\right)^{0.2}}\right)^2. \tag{35}$$

The maintainability of subsystem B is given as

$$M\left(t\right) = 1 - \exp^{-\left(\gamma_1 + H_1\right)t}. \tag{36}$$

We obtain the dependability, dependability minimum, MTBF, and MTTR of subsystem B with the help of *Eqs. (11)-(14)* presented above as $MTBF = 143hrs, MTTR = 3hrs, d = 48$ and $D_{min} = 0.9808$.

Subsystem B Analysis

Table 4. Transition table of subsystem B of the second model.

States	Status	S_0	S_1	S_2	S_3
S_0	Perfect state	0	$3\gamma_2+H_2$	0	0
S_1	Partial failure state	κ_2	0	$2\gamma_2+H_2$	0
S_2	Partial failure state	0	κ_2	0	γ_2+H_2
S_3	Complete failure state	0	0	κ_2	0

The differential equations presented below are derived using the information provided in *Table 4*.

$$\frac{d}{dt}\left(q_0(t)\right)=-\left(3\gamma_2+H_2\right)q_0+\kappa_2 q_1. \quad \textbf{(37)}$$

$$\frac{d}{dt}\left(q_1(t)\right)=\left(3\gamma_2+H_2\right)q_0-\left(2\gamma_2+H_2+\kappa_2\right)q_1+\kappa_2 q_2. \quad \textbf{(38)}$$

$$\frac{d}{dt}\left(q_2(t)\right)=\left(2\gamma_2+H_2\right)q_1-\left(\gamma_2+H_2+\kappa_2\right)q_2+\kappa_2 q_3. \quad \textbf{(39)}$$

$$\frac{d}{dt}\left(q_3(t)\right)=\left(\gamma_2+H_2\right)q_2-\kappa_2 q_3. \quad \textbf{(40)}$$

At a steady-state, *Eqs. (37)-(40)* reduce to

$$-\left(3\gamma_2+H_2\right)q_0+\kappa_2 q_1=0. \quad \textbf{(41)}$$

$$\left(3\gamma_2+H_2\right)q_0-\left(2\gamma_2+H_2+\kappa_2\right)q_1+\kappa_2 q_2=0. \quad \textbf{(42)}$$

$$\left(2\gamma_2+H_2\right)q_1-\left(\gamma_2+H_2+\kappa_2\right)q_2+\kappa_2 q_3=0. \quad \textbf{(43)}$$

$$\left(\gamma_2+H_2\right)q_2-\kappa_2 q_3=0. \quad \textbf{(44)}$$

Solving *Eqs. (41)-(44)* recursively and applying normalizing condition, we obtain

$$q_0=\frac{1}{1+\left(3y_2+r_2\right)+\left(6y_2^2+5y_2r_2+r_2^2\right)+\left(6y_2^3+11y_2^2r_2+6y_2r_2^3+r_2^3\right)},$$

$$q_1=\frac{3y_2+r_2}{1+\left(3y_2+r_2\right)+\left(6y_2^2+5y_2r_2+r_2^2\right)+\left(6y_2^3+11y_2^2r_2+6y_2r_2^3+r_2^3\right)},$$

$$q_2=\frac{6y_2^2+5y_2r_2+r_2^2}{1+\left(3y_2+r_2\right)+\left(6y_2^2+5y_2r_2+r_2^2\right)+\left(6y_2^3+11y_2^2r_2+6y_2r_2^3+r_2^3\right)},$$

and

$$q_3=\frac{6y_2^3+11y_2^2r_2+6y_2r_2^3+r_2^3}{1+\left(3y_2+r_2\right)+\left(6y_2^2+5y_2r_2+r_2^2\right)+\left(6y_2^3+11y_2^2r_2+6y_2r_2^3+r_2^3\right)},$$

where $r_2=\frac{H_2}{\kappa_2}$.

Now, the SSA of subsystem B of the second model is given as

$$Av._{subsystem-B}=\frac{1+\left(3y_2+r_2\right)+\left(6y_2^2+5y_2r_2+r_2^2\right)}{1+\left(3y_2+r_2\right)+\left(6y_2^2+5y_2r_2+r_2^2\right)+\left(6y_2^3+11y_2^2r_2+6y_2r_2^3+r_2^3\right)}. \quad \textbf{(45)}$$

In general,

$$Av._{subsystem-B}=\frac{1+\left(ny_2+r_2\right)+\left(ny_2+r_2\right)\left(\left(n-1\right)y_2+r_2\right)+...}{1+\left(ny_2+r_2\right)+\left(ny_2+r_2\right)\left(\left(n-1\right)y_2+r_2\right)+\left(ny_2+r_2\right)\left(\left(n-1\right)y_2+r_2\right)\left(\left(n-2\right)y_2+r_2\right)+...}. \quad (46)$$

Let's denote the ith term of *Eq. (46)* as T_i. Then we have

$$T_1=\left(ny_2+r_2\right),$$

$$T_2=T_1\times\left(\left(n-1\right)y_2+r_2\right)=\left(ny_2+r_2\right)\left(\left(n-1\right)y_2+r_2\right),$$

$$T_3=T_2\times\left(\left(n-2\right)y_2+r_2\right)=\left(ny_2+r_2\right)\left(\left(n-1\right)y_2+r_2\right)\left(\left(n-2\right)y_2+r_2\right),$$

$$\vdots$$

$$T_i=T_{i-1}\times\left(\left(n-i+1\right)y_2+r_2\right)=\left(ny_2+r_2\right)\left(\left(n-1\right)y_2+r_2\right)\cdots\left(\left(n-i+1\right)y_2+r_2\right).$$

Thus, using product notation, we have

$$T_i=\sum_{i=1}^{n}\prod_{j=0}^{i=1}\left(\left(n-j\right)y_2+r_2\right).$$

Thus, *Eq. (46)* reduces to

$$Av._{subsystem-B}=\frac{1+\left(ny_2+r_2\right)+\left(ny_2+r_2\right)\left(\left(n-1\right)y_2+r_2\right)+...+\sum_{i=1}^{n}\prod_{j=0}^{i=1}\left(\left(n-j\right)y_2+r_2\right)}{1+\left(ny_2+r_2\right)\left[1+\left(\left(n-1\right)y_2+r_2\right)+\left(\left(n-1\right)y_2+r_2\right)\left(\left(n-2\right)y_2+r_2\right)\right]+...+\sum_{i=1}^{n}\prod_{j=0}^{i=1}\left(\left(n-j\right)y_2+r_2\right)}. \quad (47)$$

This *Eq. (47)* will allow for the extension of the units of subsystem B if necessary.

The reliability of subsystem B of the second model is given as

$$R\left(t\right)=1-\left(1-e^{-\left(\left(\gamma_2+H_2\right)t\right)^{0.2}}\right)^2. \quad (48)$$

The maintainability of subsystem B is given as

$$M\left(t\right)=1-\exp^{-\left(\gamma_2+H_2\right)t}. \quad (49)$$

We obtain the dependability, dependability minimum, MTBF, and MTTR of subsystem B with the help of *Eqs. (11)-(14)* presented above as $MTBF=154hrs, MTTR=3hrs, d=51$ and $D_{min}=0.9819$.

3 | Numerical Simulation

In order to have inevitable guide for this study, we have validated the expressions from both models through numerical examples in this section. These validations are presented in tables and graphs ensuring clarity in our findings. For consistency, we have consistently used the following values across all instances and calculations throughout our study. Specifically, we have $\upsilon_1=0.002, \upsilon_2=0.0015, H_1=H_2=0.005,$ and $\lambda_1=\lambda_2=0.35.$

Table 5 presents a detailed RAMD analysis for the models investigated in this study, displaying a comprehensive comparison of RAMD metrics. This comparison clearly shows how well each model aligns with our research objectives and performance criteria.

Table 5. Summary of RAMD analysis results for both models.

	First Model (System)	
Performance Metrics	**Subsystem A**	**Subsystem B**
Availability	0.9999	0.9999
Reliability	$R(t)=1-\left(1-e^{-(0.002t)^{0.2}}\right)^2$	$R(t)=1-\left(1-e^{-(0.0015t)^{0.2}}\right)^2$
Maintainability	$M(t)=1-e^{-0.002t}$	$M(t)=1-e^{-0.0015t}$
Dependability	167	222
Dependability minimum	0.9942	0.9956
MTBF	500hrs	667hrs
MTTR	3hrs	3hrs
	Second Model (System)	
Performance Metrics	**Subsystem A**	**Subsystem B**
Availability	0.9998	0.9998
Reliability	$R(t)=1-\left(1-e^{-(0.007t)^{0.2}}\right)^2$	$R(t)=1-\left(1-e^{-(0.0065t)^{0.2}}\right)^2$
Maintainability	$M(t)=1-e^{-0.007t}$	$M(t)=1-e^{-0.0065t}$
Dependability	48	167
Dependability minimum	0.9808	0.9819
MTBF	143hrs	154hrs
MTTR	3hrs	3hrs

Fig. 1 illustrates the reliability trends of both subsystems within the first model, showcasing their performance over time. The graph depicts how each subsystem maintains its operational reliability throughout the observed period.

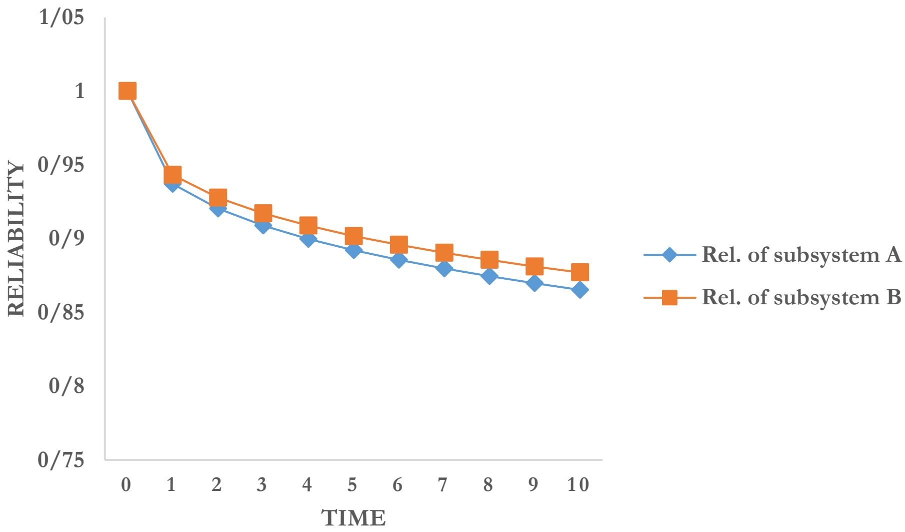

Fig. 1. The reliability of subsystems in the first model over time.

Table 6 presents a detailed analysis of maintainability metrics for both subsystems across different time intervals in the initial model. It highlights the degree of maintenance required for each subsystem, detailing the frequency and complexity of upkeep necessary to sustain their operational effectiveness over time.

Table 6. Maintainability of both subsystems in the first model over time.

Time	Maintainability of Subsystem A	Maintainability of Subsystem B
0	0.0000	0.0000
1	0.0020	0.0015
2	0.0030	0.0030
3	0.0060	0.0045
4	0.0080	0.0060
5	0.0100	0.0075
6	0.0120	0.0090
7	0.0139	0.0105
8	0.0159	0.0120
9	0.0178	0.0135
10	0.0198	0.0150

Fig. 2 illustrates the reliability performance of both subsystems in the second model. It compares their reliability within the operational context of the second model over time. This analysis helps in understanding the performance characteristics of each subsystem and their implications for the overall system reliability.

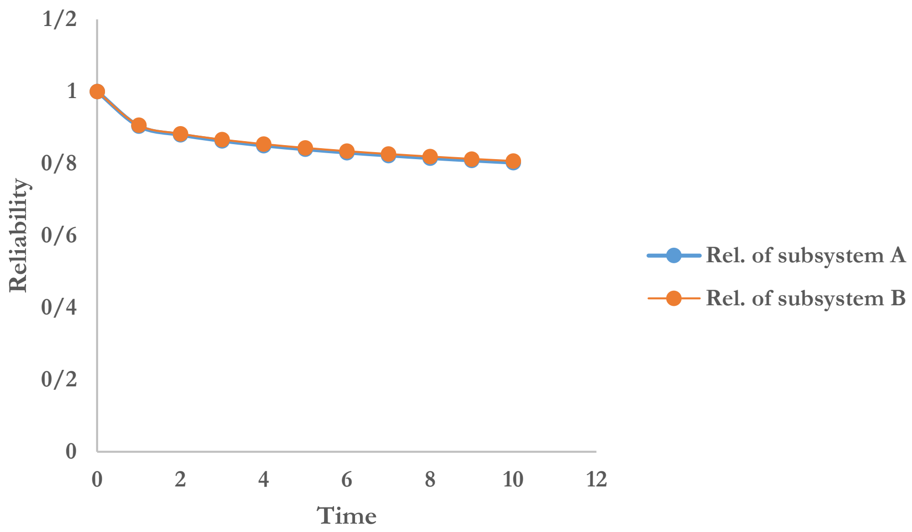

Fig. 2. The reliability of subsystems in the second model over time.

Table 7 presents the maintainability trends for both subsystems in the second model across different time intervals. These values depict the varying degrees of maintenance required to sustain each subsystem within the broader system framework. This analysis facilitates more understanding of how maintenance needs evolve throughout the system's operational lifecycle, aiding proactive management and resource allocation strategies.

Table 7. Maintainability of both subsystems in the second model over time.

Time	Maintainability of Subsystem A	Maintainability of Subsystem B
0	0.0000	0.0000
1	0.0070	0.0065
2	0.0139	0.0129
3	0.0208	0.0193
4	0.0276	0.0257
5	0.0344	0.0320
6	0.0411	0.0382
7	0.0478	0.0445
8	0.0545	0.0507
9	0.0611	0.0568
10	0.0676	0.0629

4 | Interpretation through Computational Modeling

This section presents the analysis based on the resultss presented in *Tables 5-7* and *Figs. 1* and *2* for both the models.

From *Table 5*, it is evident that both subsystems within the initial model exhibit identical availability values. This equivalence highlights their mutual necessity for ensuring successful system operation. Thus, the reliance on both subsystems becomes crucial for maintaining operational integrity. This analysis has also validated the fact that both subsystems are arranged in series, highlighting their interdependent role in the system architecture.

When maintenance is lacking/neglected in a system, its impacts its reliability. *Fig. 1* illustrates that the second subsystem in the first model exhibits higher reliability compared to the first subsystem of the same model, although both experience a decrease in reliability over time due to the absence of repairs. This emphasizes the importance of regular maintenance in maintaining operational dependability across both subsystems. The poor reliability of subsystem A implies that it plays a critical role within the system. Reliability issues in subsystem A suggest that its performance significantly influences the overall functionality and stability of the entire system. Therefore addressing reliability concerns in subsystem A becomes paramount to ensuring the overall effectiveness and dependability of the system as a whole.

The above conclusion finds support in the maintainability values for both subsystems detailed in table 6. Specifically, *Table 6* shows that subsystem A exhibits higher maintainability values compared to subsystem B. This indicates that subsystem A is more readily maintained or repaired when needed, highlighting its critical role within the system's operational reliability. The higher maintainability of subsystem A suggests that efforts to enhance its reliability through effective maintenance procedures can yield significant improvements in overall system performance and longevity.

Further observations can be drawn from *Table 1* regarding the specifications of both subsystems, A and B. Subsystem A and B are characterized by different metrics that contribute to their operational reliability. Subsystem A, for instance, is specified with a dependability rating of 167 and a minimum dependability value of 0.9942. Its MTBF is recorded at 500 hours, with a MTTR of 3 hours. In comparison, subsystem B exhibits a higher dependability rating of 222 and a minimum Dependability value of 0.9956. Its MTBF extends to 667 hours, similarly with an MTTR of 3 hours. These specifications highlight the different strengths and capabilities of each subsystem. Subsystem A, despite having slightly lower dependability and a shorter MTBF compared to subsystem B, maintains a robust capability with a reliable MTTR. Subsystem B, on the other hand, showcases superior dependability metrics and a longer MTBF, indicating potentially fewer failures over extended periods.

Similar observations to those seen in the first model are also evident in *Table 1, Table 6,* and *Fig. 2* of the second model, which involves two human operators, suggesting a coherent trend across various data points analyzed in the study.

Upon comparison, the first model exhibits superior performance relative to the second model, which incorporates two human operators. This highlights a critical managerial concern. The influence of human operator numbers on model effectiveness. Maintenance managers and system engineers should thoroughly evaluate these factors when making decisions about resource allocation and operational strategies.

5 | Conclusion

In conclusion, our RAMD analysis comparing two hybrid models reveals that the first system, with two subsystems A and B, each with a different number of active units, performs better than the second system. Despite similar subsystem configurations in both systems, the absence of distinct human operators in the first system appears advantageous over the second system, where individual operators manage each subsystem. furthermore, the analysis also reveals that in both systems under consideration, subsystem A exhibits poor reliability. This consistent observation highlights a significant reliability issue across both models, indicating a critical area for improvement. Addressing the reliability challenges in subsystem A and thoughtful consideration of human involvement in model implementation can lead to enhanced overall system performance and operational efficiency.

Future research should focus on identifying the root causes of this reliability issue, integrating human operator and implementing targeted solutions to reduce their impact on system reliability and functionality.

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Authors' Contribution

The study's conception and design were contributed to by the authors. Material preparation, analysis and discussion of results were done by the named author. All authors have read and approved the manuscript.

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Availability of Data and Materials

The authors declare that all the data and materials supporting the findings of this study are available within the article.

Declarations

Consent for publication

Not applicable

Conflict of Interests

The authors whose names are written on this manuscript certify that they have NO affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

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