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Reliability Availability Maintainability and Dependability Analysis of Solar Photovoltaic Systems for Community Water Supply

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Abstract

This study investigates the reliability, maintainability, availability, and dependability of a series-parallel photovoltaic system comprising four subsystems: solar panels, inverters, water pumping machines, and tanks. By employing transition diagrams and the system of linear differential-difference equations are established. The primary objective is to analyze the system's reliability metrics and assess how system parameters influence its performance. Critical subsystems are identified based on these evaluations. Numerical analysis reveals insights into the system's performance, suggesting optimal reliability occurs when overall failure rates are minimized, and support units are effectively activated.

Keywords: Community, Water, Photovoltaic, Supply.

1 | Introduction

Water supply is a vital aspect of community life, essential for daily activities. The consistency and reliability of water provision are key indicators of an environment's standard and efficiency. It's widely recognized that both individual units and larger systems, comprising diverse components, experience failures over time due to random factors. Probabilistic events, derived from random experiments, serve as valuable tools for statistically predicting future system behavior. Numerous studies have proposed analytical approaches to assess the strength and efficiency of the systems across various environmental conditions. These systems typically feature interconnected components/subsystems in series-parallel configurations, with units

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operating in active parallel, standby, or k-out-of-n arrangements. The failure of any subsystem can result in significant system disruptions, leading to costly maintenance. Given the critical role of series-parallel systems in product quality, production output, and revenue generation, researchers have increasingly focused on reliability analysis to enhance system performance and longevity.

Numerous researchers have delved into a myriad of approaches aimed at comprehensively analyzing the strength and efficiency of systems within the realms of solar photovoltaic technology and solar water pumping systems. These investigations have spanned a wide array of scenarios and environmental conditions, reflecting the diverse challenges and requirements inherent in these fields. Researchers have diligently explored various methodologies, ranging from theoretical frameworks to practical simulations, in order to dissect and understand the intricacies of these systems. Through rigorous experimentation, modeling, and data analysis, they have sought to uncover the underlying factors influencing system performance and reliability. These efforts have yielded invaluable insights into optimizing system design, operation, and maintenance practices, thereby contributing to the advancement of sustainable and dependable solar energy solutions.

Several notable contributions have emerged within system reliability and performance analysis. For instance, Malhotra and Taneja [1] undertook pioneering work by developing and meticulously comparing reliability models tailored to varying demand cold standby systems. Their research shed light on the intricate dynamics of such systems, providing valuable insights into their reliability characteristics and operational effectiveness. Similarly, Singh and Ayagi [2] made significant strides in the field with their groundbreaking models designed for the performance analysis of complex repairable systems under pre-emptive resume repair strategies. By delving into the complexities of repairable systems and incorporating preemptive repair strategies into their models, Singh and Ayagi advanced the state-of-the-art in understanding and optimizing the performance of such systems. Their work not only expanded the theoretical framework but also offered practical implications for enhancing system reliability and efficiency in real-world applications. These exemplary studies represent just a fraction of the extensive research efforts aimed at advancing the understanding and analysis of system reliability and performance in the context of solar photovoltaic and solar water pumping systems. Collectively, they underscore the interdisciplinary nature of this field and highlight the ongoing quest for innovative methodologies and insights to address the pressing challenges and opportunities in sustainable energy systems.

Lado and Singh [3] embarked on an extensive inquiry into the evaluation of expenses related to intricate systems managed by human operators. Their study delved into the complexities surrounding human involvement in system operation and upkeep, presenting valuable perspectives on the economic implications and cost determinants affecting the overall efficiency and dependability of such systems.

Garg [4] made notable advancements in the field through the development and rigorous examination of a dual-objective optimization model specifically tailored for series-parallel systems. Employing sophisticated mathematical modeling and optimization methodologies, Garg's research introduced an innovative framework aimed at concurrently addressing reliability and cost considerations in the design and administration of series-parallel systems. This work provided tangible solutions for enhancing system performance and economic viability.

Yusuf et al. [5] conducted an exhaustive investigation into the reliability and operational efficacy of series-parallel systems utilizing copula-based methodologies. Leveraging copula functions, their study presented a robust approach to capturing the interdependence among system elements and evaluating the overall reliability and performance attributes of the series-parallel configurations. Their findings offered valuable insights into the interconnectedness of system components and their impact on system reliability across diverse operational scenarios.

Malhotra et al. [6] conducted a comprehensive analysis examining the cold standby systems reliability comprising two units, employing a preventive maintenance approach. Through meticulous modeling and analysis, their study elucidated the efficacy of proactive maintenance measures in averting system failures and enhancing reliability within redundant cold standby setups. Their findings provided valuable insights into optimizing maintenance strategies to bolster the reliability and availability of critical systems across various application domains.

Maintainability, Availability, Reliability, and Dependability (MARD) represent fundamental pillars in the evaluation and optimization of system performance across industries. These metrics serve as indispensable tools in the arsenal of plant management, enabling them to gauge the efficacy and resilience of their systems and to implement targeted interventions for improvement. RAMD analysis serves as a strategic framework through which plant management can discern the critical components or subsystems within a system requiring prioritized maintenance interventions. By identifying and addressing these areas proactively, plant managers can bolster the overall performance and longevity of the system. This analytical approach entails evaluating the system at various stages of its lifecycle, employing a diverse array of performance modeling methodologies tailored to the specific context and requirements of the system under scrutiny.

Through systematic RAMD analysis, significant performance indicators are derived, offering invaluable insights into the operational dynamics of the system. Among the key metrics derived from RAMD evaluation are Mean Time Between Repairs (MTBR) and Mean Time To Repair (MTTR), which provide crucial insights into the frequency and duration of downtime experienced by the system. Availability, reliability, and maintainability metrics offer further granularity, shedding light on the system's ability to deliver optimal performance consistently and to recover from potential failures swiftly.

Ensuring the reliability and availability of systems while enhancing their features represents a paramount goal for engineers, and the Reliability, Availability, Maintainability, and Dependability (RAMD) approach stands as a cornerstone in achieving this objective. Building upon this premise, researchers have diligently pursued the development of diverse maintenance frameworks and tactics aimed at optimizing system performance and bolstering RAMD metrics.

The notable contribution comes from Corvaro et al. [7], who conducted a comprehensive study focusing on the maintainability, availability and reliability aspects of reciprocating compressors. Their research delved into the intricacies of these critical components, exploring methodologies to enhance their operational reliability and minimize downtime. Through rigorous analysis and experimentation, Corvaro et al. offered valuable insights into optimizing maintenance practices and improving the overall RAMD profile of reciprocating compressors.

Similarly, Kumar and Tewari [8] conducted a thorough review of various approaches for evaluating system performance, with a particular emphasis on reliability, availability, and maintainability considerations. Drawing from a wide range of literature sources, they synthesized key methodologies and best practices employed in assessing and optimizing system RAMD metrics. By providing a comprehensive overview of existing approaches, Kumar and Tewari's work serves as a valuable resource for engineers and researchers striving to enhance system reliability and availability through effective maintenance strategies.

In his extensive study, Tsarouhas [9] delved deeply into the intricacies surrounding the maintainability, availability and reliability of a wine packaging production system. With meticulous attention to detail, Tsarouhas meticulously scrutinized the operational intricacies of the system, unearthing valuable insights into its functionality and performance dynamics. By conducting a thorough examination, Tsarouhas not only elucidated the operational challenges but also proposed strategic interventions aimed at enhancing system performance and optimizing RAMD metrics. Through his comprehensive analysis, Tsarouhas provided practical strategies and recommendations for improving the maintainability, availability and reliability of the wine packaging production system, thereby contributing to the advancement of operational efficiency and effectiveness in the wine industry.

In their groundbreaking work, some reseachers dedicated their efforts to crafting specialized models aimed at evaluating the performance of industrial systems via the implementation of the MARD approach. Their pioneering research marked a significant milestone in the field, as it not only expanded the methodological repertoire for assessing system performance but also propelled advancements in the optimization of system reliability, availability, and maintainability.

Taleb-Berrouane et al. [10] embarked on an innovative journey by employing a probabilistic framework to assess the availability, maintainability, and reliability of a complex system. By harnessing the power of probabilistic methodologies, their research illuminated the intricate performance characteristics inherent within the system, shedding light on its operational dynamics and vulnerabilities. Through the application of probabilistic analysis, Taleb-Berrouane et al. uncovered valuable insights into the availability, maintainability, and reliability of the system, providing stakeholders with a deeper understanding of its performance under various conditions. Their study not only identified potential areas of weakness but also offered strategic guidance for fortifying the system's operational resilience and efficiency. By leveraging probabilistic methodologies, Taleb-Berrouane et al. transcended traditional deterministic approaches, enabling a more nuanced and comprehensive evaluation of system performance. Their research paved the way for more sophisticated risk management strategies and proactive maintenance interventions, ultimately enhancing the system's ability to withstand uncertainties and unforeseen challenges.

Choudhary et al. [11] undertook an analysis centered on the availability, maintainability, and reliability of a cement plant. Their investigation illuminated the operational intricacies inherent in cement production processes, providing valuable strategies to optimize system performance and elevate RAMD metrics within industrial contexts.

Monika and Ashish [12] scrutinized the performance of an evaporating unit in a sugar manufacturing plant, employing the RAMD approach. Their analysis yielded valuable insights into enhancing the operation of evaporating units, thereby enhancing the overall efficiency and reliability of sugar manufacturing processes.

Saini et al. [13] investigated the RAMD of microprocessor systems, thereby advancing the comprehension and refinement of system reliability, availability, and maintainability within microprocessor-based applications. Reena and Basotia [14] devised performance models intended for evaluating the robustness of a cement manufacturing plant. Their study furnished invaluable insights into streamlining plant operations and fortifying overall performance and reliability. Sanusi and Yusuf [15] applied the RAMD technique to analyze the performance of a computer-based test at the subsystem level. Their findings provided strategic insights for enhancing the reliability, availability, and maintainability of the test system, thereby optimizing its overall performance.

Gupta et al. [16] delved into the investigation of the availability, maintainability, and reliability of a generator within a steam turbine power plant. Their study played a pivotal role in augmenting the comprehension and refinement of power generation system reliability and availability optimization. Barma and Modibbo [17] introduced a multi-objective optimization model tailored for a solid waste management system. Their research offered pragmatic strategies aimed at enhancing system performance while concurrently optimizing resource utilization and mitigating environmental impact. Jagtap et al. [18] conducted an analysis focusing on the availability, maintainability, and reliability optimization of a thermal power plant. Through their study, they provided valuable insights into enhancing power plant performance and operational efficiency through strategic optimization strategies.

Khan et al. [19] delved into a performance measure decision-making approach tailored for T-spherical operators, thereby enriching decision-making processes aimed at enhancing system performance and reliability. Garg and Garg [20] deliberated on the optimization of profit and availability within a single-unit system featuring imperfect switchover. Their discussion provided actionable strategies for maximizing system profitability while ensuring optimal availability. Danjuma et al. [21] conducted a comprehensive study on the availability, maintainability, and reliability analysis of cold standby series-parallel systems. Their research significantly contributed to advancing the understanding and optimization of system reliability and availability within intricate industrial setups.

The majority of studies examining RAMD in energy systems tend to concentrate on conventional energy sources, such as the electric grid, generators, and tractors. These sources often entail high handling costs, and their failure can have severe repercussions on community water supply systems. However, there is a noticeable dearth of research focusing on the implementation and performance analysis of solar photovoltaic community water systems. These solar photovoltaic community water systems typically encompass a range of components, including solar panels, inverters, water pumping machines, and tanks. Despite their potential to offer sustainable and cost-effective solutions for community water supply, there remains a gap in understanding their RAMD characteristics and overall performance. Addressing this gap is essential as it offers insights into the implications and feasibility of integrating solar photovoltaic systems into community water supply infrastructure. By conducting thorough RAMD and performance analyses, researchers can assess the availability, maintainability, reliability, and dependability of these systems under various operating conditions.

Moreover, understanding the RAMD profile of solar photovoltaic community water systems is crucial for ensuring reliable and uninterrupted water supply to communities, particularly in areas where access to conventional energy sources may be limited or unreliable. Additionally, such analyses can inform decision-making processes related to system design, operation, and maintenance, ultimately contributing to the optimization of community water supply infrastructure.

In light of the above considerations, this paper undertakes an examination of a solar photovoltaic community water system, which comprises four distinct subsystems: solar panels, inverters, water pumping machines, and tanks, configured in a series-parallel arrangement. The performance of this system is meticulously scrutinized utilizing first-order differential-difference equations. Key performance metrics, including reliability, availability, maintainability, Mean Time To Failure (MTTF), and Mean Time Between Failure (MTBF), are computed to gauge the system's strength and effectiveness across each subsystem.

The objectives of this paper are delineated into four main components. Firstly, the aim is to devise innovative models for maintainability, availability, reliability and Dependability analysis specific to solar photovoltaic community water systems. Secondly, explicit expressions are developed for crucial performance metrics, such as availability, reliability, MTTF, maintainability, MTTF, and dependability, for each subsystem within the solar photovoltaic community water system.

Furthermore, the study endeavors to assess the system's performance using RAM models under the exponentiated Weibull distribution, offering insights into the system's behavior under varying conditions. Lastly, the paper aims to elucidate the impact of time, failure rates, and repair rates on system reliability, maintainability, and availability, thereby providing a comprehensive understanding of the factors influencing the operational dynamics of the solar photovoltaic community water system. Through these multifaceted objectives, the paper seeks to contribute significantly to the body of knowledge surrounding the RAMD analysis and performance evaluation of solar photovoltaic community water systems, ultimately advancing the understanding and optimization of community water supply infrastructure.

2 | Material and Methods

Reliability

The chance that the photovoltaic system for community water supply is good at the passage of time is the reliability. Thus, the reliability of photovoltaic systems is given by

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

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

for exponential distribution.

Availability is given by

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

Maintainability

When the maintenance is observed fluently to the need level is referred to as system maintainability.

$$M(t) = P(T \leq t) = 1 - e^{-rt}. \tag{4}$$

Where r is the rate of repair of the system.

Dependability is defined as

$$D_{min} = 1 - \left(\frac{1}{d-1}\right)\left(e^{-In\frac{d}{d-1}} - e^{-dIn\frac{d}{d-1}}\right). \tag{5}$$

For $d = \frac{\text{rate of repair}}{\text{rate of failure}}$.

MTTR is defined as

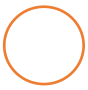
$$MTTR = \frac{1}{\text{rate of repair}}.$$

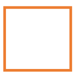
MTBF is given by

$$MTBF = \frac{1}{\text{rate of failure}}. \tag{6}$$

3 | Notations and Description of the System

3.1 | Notations

 system is good

 system is down

r_i: denote rate of repair.

a_i: rate of failure for some i = 1,2,3,4.

Q_0: system is in the initial probability state.

Q_i: system is staying in state i^{th} state.

3.2 | Description of the System

The system under consideration in this study is a photovoltaic system designed specifically for community water supply purposes. This system operates in a serial configuration, comprising several key components aimed at harnessing solar energy efficiently and delivering clean water to the community. The core elements of this system include:

Solar panels: subsystem saddled with responsibility for converting solar energy into electricity. Typically composed of photovoltaic cells, solar panels capture sunlight and convert it into Direct Current (DC) electricity.

Inverters: an inverter serves the same fundamental purpose as any other solar PV system: it converts the DC electricity generated by the solar panels into Alternating Current (AC) electricity. However, in this specific application, the electricity produced by the solar panels is typically used to power water pumps or other water treatment equipment required for the community water supply system.

Water pumping machines: these machines are essential for drawing water from its source, such as wells, boreholes, or reservoirs, and delivering it to the community. They are typically powered by electricity and play a central role in ensuring a continuous and reliable water supply.

Storage Tanks: Storage tanks serve as reservoirs for holding the pumped water before it is distributed to the community. These tanks help regulate the flow of water, ensuring that there is a consistent supply available to meet the needs of the community, even during periods of limited sunlight or increased demand.

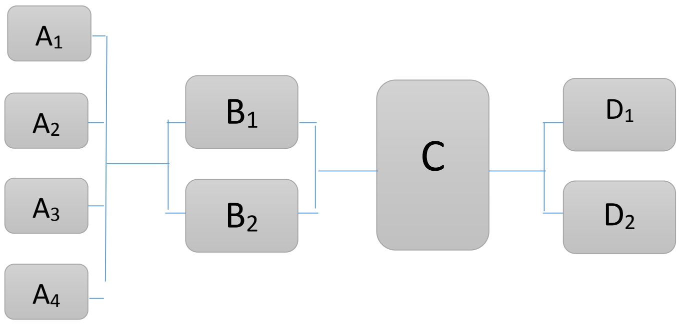


Fig. 1. Schematic diagram of Photovoltaic system.

Table 1. Values of parameters used.

Subsystem	Failure Rate (a)	Repair Rate (r)
Solar panel	a1 = 0.0013	r1 = 0.45
Inverter	a2 = 0.005	r2 = 0.082
Water pumping machine	a3 = 0.003	r3 = 0.86
Reservoir/Tank	a4 = 0.0052	r4 = 0.82

Parameter values in the above table will be used to validate the computed models of the study.

4 | Formulation of MARD Models for Photovoltaic System

In this section, MARD performance models are formulated.

4.1 | Formulation of RAMD Models for Panel Subsystem

Solar panels are the primary component of solar-powered water pumping systems, as they are responsible for converting sunlight into electricity that powers the system. The efficiency and capacity of the solar panels are crucial factors that affect the system's overall performance. The PV panel subsystem has four panels in active parallel. *Eqs. (13)-(17)* are derived using the Markovian birth-death process.

$$\frac{dQ_0(t)}{dt} = -4a_1Q_0 + r_1Q_1. \tag{7}$$

$$\frac{dQ_1(t)}{dt} = -(3a_1 + r_1)Q_1 + 4a_1Q_0 + r_1Q_2. \tag{8}$$

$$\frac{dQ_2(t)}{dt} = -(2a_1 + r_1)Q_2 + 3a_1Q_1 + r_1Q_3. \tag{9}$$

$$\frac{dQ_3(t)}{dt} = -(a_1 + r_1)Q_3 + 2a_1Q_2 + r_1Q_4. \tag{10}$$

$$\frac{dQ_4(t)}{dt} = -a_1Q_4 + r_1Q_3. \tag{11}$$

Solving (8)–(12) in a stable state

$$-4a_1Q_0 + r_1Q_1 = 0. \quad \textbf{(12)}$$

$$-(3a_1 + r_1)Q_1 + 4a_1Q_0 + r_1Q_2 = 0. \quad \textbf{(13)}$$

$$-(2a_1 + r_1)Q_2 + 3a_1Q_1 + r_1Q_3 = 0. \quad \textbf{(14)}$$

$$-(a_1 + r_1)Q_3 + 2a_1Q_2 + r_1Q_4 = 0. \quad \textbf{(15)}$$

$$-a_1Q_4 + r_1Q_3 = 0. \quad \textbf{(16)}$$

Implementing the sum of all probabilities given as

$$Q_0 + Q_1 + Q_2 + Q_3 + Q_4 = 1.$$

We have

$$Q_0 = \left(1 + \frac{4a_1}{r_1} + \frac{12a_1^2}{r_1^2} + \frac{24a_1^3}{r_1^3} + \frac{24a_1^4}{r_1^4}\right)^{-1}.$$

$$Q_1 = \frac{4a_1}{r_1}Q_0,$$

$$Q_2 = \frac{12a_1^2}{r_1^2}Q_0,$$

$$Q_3 = \frac{24a_1^3}{r_1^3}Q_0,$$

$$Q_4 = \frac{24a_1^4}{r_1^4}Q_0.$$

And

$$R(t) = e^{-at}. \quad \textbf{(17)}$$

The reliability of the panel subsystem and the entire system is computed as follows:

$$R(t) = e^{-a_1t}. \quad \textbf{(18)}$$

$$R_{S_A}(t) = e^{-0.0013t}. \quad \textbf{(19)}$$

With availability computed as

$$A_{C_A}(t) = Q_0 + Q_1 + Q_2 + Q_3. \quad \textbf{(20)}$$

$$A_{C_A}(t) = \left(\frac{1 + \frac{4a_1}{r_1} + \frac{12a_1^2}{r_1^2} + \frac{24a_1^3}{r_1^3}}{1 + \frac{4a_1}{r_1} + \frac{12a_1^2}{r_1^2} + \frac{24a_1^3}{r_1^3} + \frac{24a_1^4}{r_1^4}}\right) = 0.9999. \quad \textbf{(21)}$$

Maintainability of subsystem A as

$$M(t) = P(T \leq t) = 1 - e^{-rt}. \quad \textbf{(22)}$$

$$M(t) = 1 - e^{-r_1t}. \quad \textbf{(23)}$$

$$M_{C_A}(t) = 1 - e^{-0.45t}. \quad \textbf{(24)}$$

$\text{MTBF} = 769.230\text{h}$, $\text{MTTR} = 2.222\text{h}$, $d = 346.188$, $D_{\min_{CA}} = 0.9981$.

4.2 | Formulation of RAMD Models for Subsystem B

Eqs. (16)-(25) below are derived using the Markovian birth-death process.

$$\frac{dQ_0(t)}{dt} = -2a_2Q_0 + r_2Q_1. \quad (25)$$

$$\frac{dQ_1(t)}{dt} = -(a_2 + r_2)Q_1 + 2a_2Q_0 + r_2Q_2. \quad (26)$$

$$\frac{dQ_2(t)}{dt} = -a_1Q_2 + r_2Q_1. \quad (27)$$

Solving (25)–(27) in a stable state $\frac{dQ_i(t)}{dt} = 0$,

$$-2a_2Q_0 + r_2Q_1 = 0. \quad (28)$$

$$-(a_2 + r_2)Q_1 + 2a_2Q_0 + r_2Q_2 = 0. \quad (29)$$

$$-a_1Q_2 + r_2Q_1 = 0. \quad (30)$$

By applying the normalizing condition

$$Q_0 + Q_1 + Q_2 = 1.$$

We have

$$Q_0 = \left(1 + \frac{a_2}{r_2} + \frac{a_1^2}{r_1^2}\right)^{-1}.$$

$$Q_1 = \frac{a_2}{r_2}Q_0.$$

$$Q_2 = \frac{a_2^2}{r_2^2}Q_0.$$

The reliability of subsystem B, the entire system, availability, and maintainability are computed as

$$R(t) = e^{-at}. \quad (31)$$

$$R(t) = e^{-a_2t}. \quad (32)$$

$$R_{C_B}(t) = e^{-0.005t}. \quad (33)$$

$$A_{C_B}(t) = Q_0 + Q_1. \quad (34)$$

$$A_{C_B}(t) = \left(\frac{a_2^2 + a_2r_2}{a_2^2 + a_2r_2 + r_2^2}\right) = 0.9965. \quad (35)$$

$$M(t) = P(T \leq t) = 1 - e^{-rt}. \quad (36)$$

$$M(t) = 1 - e^{-r_2t}. \quad (37)$$

$$M_{C_B}(t) = 1 - e^{-0.082t}. \quad (38)$$

The following are other performance indicators of subsystem B:

$MTBF = 200h$, $MTTR = 12.20h$, $d = 16.393$, $D_{min_{CB}} = 0.9492$.

4.3 | Formulation of RAMD Models for Subsystem C

This subsystem has a single active water-pumping machine. The failure of the water pumping machine results in to collapse of the system.

$$\frac{dQ_0(t)}{dt} = -a_3Q_0 + r_3Q_1. \tag{39}$$

$$\frac{dQ_1(t)}{dt} = -a_3Q_1 + r_3Q_0. \tag{40}$$

Solving (39)–(40) in a stable state $\frac{dS_i(t)}{dt} = 0$,

$$-a_3Q_0 + r_3Q_1 - \alpha_3 = 0. \tag{41}$$

$$-a_3Q_1 + r_3Q_0 = 0. \tag{42}$$

By applying the normalizing condition

$$Q_0 + Q_1 = 1.$$

We have

$$Q_0 = \frac{r_3}{r_3 + a_3}.$$

$$Q_1 = \frac{a_3}{r_3}Q_0.$$

The reliability of subsystem C, the entire system, availability, and maintainability are computed as

$$R(t) = e^{-at}. \tag{43}$$

$$R(t) = e^{-a_3t}. \tag{44}$$

$$A_{C_C}(t) = Q_0. \tag{45}$$

$$A_{C_C}(t) = \left(\frac{r_3}{r_3 + a_3}\right) = 0.9965. \tag{46}$$

$$M(t) = P(T \leq t) = 1 - e^{-rt}. \tag{47}$$

$$M(t) = 1 - e^{-r_3t}. \tag{48}$$

$$M_{C_C}(t) = 1 - e^{-0.086t}. \tag{49}$$

The following are other performance indicators of subsystem C:

MTBF = 333.333h, MTTR = 1.163h, d = 286.6155 $D_{minC_C} = 0.9966$.

4.4 | Formulation of RAMD Models for Subsystem D

Eqs. (57)-(59) below are derived using the Markovian birth-death process.

$$\frac{dQ_0(t)}{dt} = -2a_4Q_0 + r_4Q_1. \tag{50}$$

$$\frac{dQ_1(t)}{dt} = -(a_4 + r_2)Q_1 + 2a_4Q_0 + r_4Q_2. \tag{51}$$

$$\frac{dQ_2(t)}{dt} = -a_4Q_2 + r_4Q_1. \tag{52}$$

Solving (51)–(53) in a stable state $\frac{dQ_i(t)}{dt} = 0$,

$$-2a_4Q_0 + r_4Q_1 = 0. \tag{53}$$

$$-(a_4 + r_4)Q_1 + 2a_4Q_0 + r_4Q_2 = 0. \tag{54}$$

$$-a_4Q_2 + r_4Q_1 = 0. \tag{55}$$

By applying the normalizing condition

$$Q_0 + Q_1 + Q_2 = 1.$$

We have

$$Q_0 = \left(1 + \frac{a_4}{r_4} + \frac{a_4^2}{r_4^2}\right)^{-1},$$

$$Q_1 = \frac{a_4}{r_4} Q_0,$$

$$Q_2 = \frac{a_4^2}{r_4^2} Q_0.$$

The reliability of subsystem D, the entire system, availability, and maintainability are computed as

$$R(t) = e^{-at}. \tag{56}$$

$$R(t) = e^{-a_4 t}. \tag{57}$$

$$R_{C_D}(t) = e^{-0.0052t}. \tag{58}$$

$$A_{C_D}(t) = Q_0 + Q_1. \tag{59}$$

$$A_{C_D}(t) = \left(\frac{a_4^2 + a_4 r_2}{a_4^2 + a_4 r_2 + r_4^2}\right) = 0.9492. \tag{60}$$

$$M(t) = P(T \le t) = 1 - e^{-rt}. \tag{61}$$

$$M(t) = 1 - e^{-r_4 t}. \tag{62}$$

$$M_{C_D}(t) = 1 - e^{-0.082t}. \tag{63}$$

The following are other performance indicators of subsystem D:

$\mathrm{MTBF} = 200\mathrm{h}, \mathrm{MTTR} = 12.20\mathrm{h}, d = 16.393, D_{\min_{CD}} = 0.9492.$

5 | Numerical Simulation

In this section, we validate the computed models and emphasize the optimality of the results through the presentation of numerical findings in tables and figures.

5.1 | RAMD Indices for Subsystem

The reliability of the system is computed as

$$R_{Sys}(t) = R_{C_A}(t) * R_{C_B}(t) * R_{C_C}(t) * R_{C_D}(t). \tag{64}$$

$$R_{Sys}(t) = (e^{-0.0013t})(e^{-0.005t})(e^{-0.003t})(e^{-0.0052t}). \tag{65}$$

$$R_{Sys}(t) = e^{-0.0613t}. \tag{66}$$

Availability of the system is computed as

$$A_{Sys}(t) = A_{C_A}(t) * A_{C_B}(t) * A_{C_C}(t) * A_{C_D}(t). \tag{67}$$

$$A_{Sys}(t) = \left(\frac{1+\frac{4a_1}{r_1}+\frac{12a_1^2}{r_1^2}+\frac{24a_1^3}{r_1^3}}{1+\frac{4a_1}{r_1}+\frac{12a_1^2}{r_1^2}+\frac{24a_1^3}{r_1^3}+\frac{24a_1^4}{r_1^4}}\right)\left(\frac{a_2^2+a_2r_2}{a_2^2+a_2r_2+r_2^2}\right)\left(\frac{r_3}{r_3+r_3}\right)\left(\frac{a_4^2+a_4r_2}{a_4^2+a_4r_2+r_4^2}\right) = 0.9894. \tag{68}$$

Maintainability of the system is

$$M_{Sys}(t) = M_{C_A}(t) * M_{C_B}(t) * M_{C_C}(t) * M_{C_D}(t). \quad (69)$$

$$M_{Sys}(t) = (1 - e^{-0.45t})(1 - e^{-0.082t})(1 - e^{-0.086t})(1 - e^{-0.082t}). \quad (70)$$

$$M_{Sys}(t) = 1 - e^{-0.7t}. \quad (71)$$

The dependability of the system is

$$D_{min_{Sys}} = D_{min_{SA}} * D_{min_{SB}} * D_{min_{SC}} * D_{min_{SD}}. \quad (72)$$

$$D_{min_{Sys}} = (0.9981)(0.9492)(0.9966)(0.9492) = 0.8962. \quad (73)$$

Table 2. RAMD Indices for subsystems.

Indices	Subsystem			
	A	**B**	**C**	**D**
Reliability	$e^{-0.0013t}$	$e^{-0.005t}$	$e^{-0.003t}$	$e^{-0.0052t}$
Availability	0.999999	0.996565	0.996565	0.9965
Maintainability	$1 - e^{-0.45t}$	$1 - e^{-0.082t}$	$1 - e^{-0.086t}$	$1 - e^{-0.082t}$
Dependability ratio	346.18888	16.39393	286.61616	16.393
MTBF	769.2323	20000	333.33333	200
MTTR	2.22222	12.2020	1.16363	12.20
Dependability min	0.998181	0.949292	0.996666	0.9492

Table 3. Reliability variation over time.

Time (t) in Hours	$R_{S_A}(t)$	$R_{S_B}(t)$	$R_{S_C}(t)$	$R_{S_D}(t)$	$R_{S_{Sys}}(t)$
0	1.000000	1.000000	1.000000	1.000000	1.0000
10	0.987171	0.951212	0.970404	0.949393	0.8650
20	0.974343	0.904848	0.941818	0.901212	0.7572
30	0.961818	0.860707	0.913939	0.855656	0.6473
40	0.949393	0.818787	0.886969	0.812222	0.6509
50	0.937171	0.778888	0.860707	0.771111	0.4845
60	0.925050	0.740808	0.835353	0.732020	0.4189
70	0.913030	0.704747	0.810606	0.694949	0.3624
80	0.901212	0.670303	0.786666	0.659797	0.3135
90	0.889696	0.637676	0.763434	0.626363	0.2712

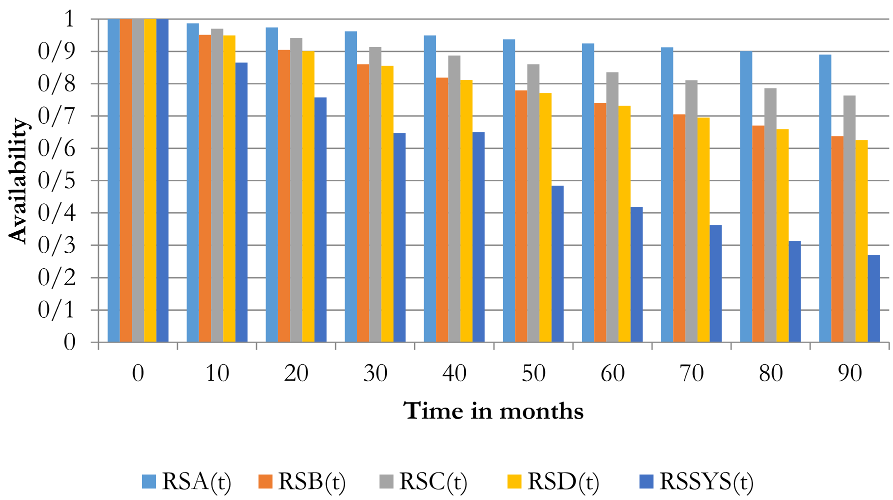


Fig. 2. Availability comparison between subsystems and the entire system.

Table 4. Maintainability variation over time.

Time(t) in Hours	$M_{S_A}(t)$	$M_{S_B}(t)$	$M_{S_C}(t)$	$M_{S_D}(t)$	$M_{S_{Sys}}(t)$
0	0.000000	0.000000	0.000000	0.000000	0.0000
10	0.988989	0.559595	0.493434	0.559595	0.9991
20	0.999898	0.806060	0.743333	0.806060	0.9999
30	0.999999	0.914545	0.869999	0.914545	0.9999
40	0.999999	0.962424	0.934141	0.962424	1.0000
50	0.999999	0.983434	0.966666	0.983434	1.0000
60	0.999999	0.992727	0.983131	0.992727	1.0000
70	1.000000	0.996868	0.991414	0.996868	1.0000
80	1.000000	0.998686	0.995757	0.998686	1.0000
90	1.000000	0.999494	0.997878	0.999494	1.0000

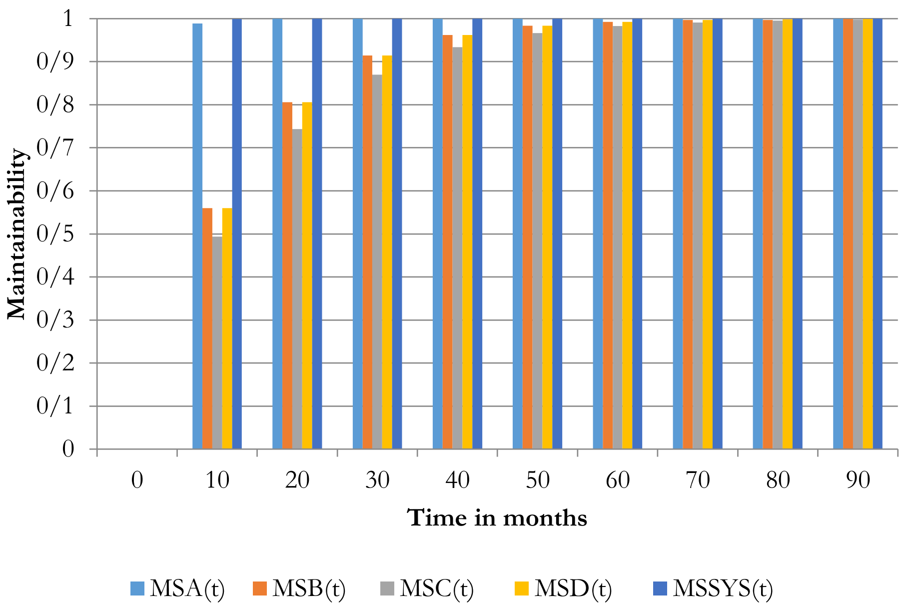


Fig. 3. Maintainability comparison between subsystems and the entire system.

Table 5. Reliability variation of panel and photovoltaic system over time.

Time (t) in Hours	Subsystem		System	
	$\alpha_1 = 0.0002$	$\alpha_1 = 0.0004$	$\alpha_1 = 0.0002$	$\alpha_1 = 0.0004$
0	1.000000	1.000000	1.000000	1.0000
10	0.998080	0.996060	0.874545	0.8727
20	0.996060	0.992323	0.872727	0.8695
30	0.994040	0.988181	0.871010	0.8658
40	0.992020	0.984141	0.869292	0.8623
50	0.990000	0.980101	0.867575	0.8588
60	0.988181	0.976363	0.865858	0.8555
70	0.986161	0.972424	0.864141	0.8521
80	0.984141	0.968585	0.862323	0.8486
90	0.982222	0.964646	0.860606	0.8452

Table 6. Reliability variation of Inverter and Photovoltaic system over time.

Time (t) in Hours	Subsystem		System	
	$\alpha_2 = 0.0006$	$\alpha_2 = 0.0008$	$\alpha_2 = 0.0006$	$\alpha_2 = 0.0008$
0	1.000000	1.000000	1.000000	1.0000
10	0.994040	0.992020	0.903939	0.9020
20	0.988181	0.984141	0.898585	0.8945
30	0.982222	0.976262	0.893131	0.8877
40	0.976363	0.968585	0.887878	0.8807
50	0.970404	0.960808	0.882424	0.8737
60	0.964646	0.953131	0.877171	0.8667
70	0.958989	0.945555	0.871919	0.8598
80	0.953131	0.938080	0.866767	0.8529
90	0.947474	0.930505	0.861515	0.8461

Table 7. Reliability variation UMP and Photovoltaic system over time.

Time (t) in Hours	Subsystem		System	
	$\alpha_3 = 0.002$	$\alpha_3 = 0.004$	$\alpha_3 = 0.002$	$\alpha_3 = 0.004$
0	1.000000	1.000000	1.000000	1.0000
10	0.980202	0.960808	0.873737	0.8564
20	0.960808	0.923131	0.856464	0.8228
30	0.941818	0.886969	0.839595	0.7905
40	0.923131	0.852121	0.822828	0.7595
50	0.904444	0.818787	0.806161	0.7297
60	0.886969	0.786666	0.790505	0.7011
70	0.869494	0.755858	0.774949	0.6737
80	0.852121	0.726161	0.759595	0.6472
90	0.835353	0.697878	0.744545	0.6219

Table 8. Reliability variati Tank and Photovoltaic system over time.

Time(t) in Hours	Subsystem		System	
	$\alpha_4 = 0.006$	$\alpha_4 = 0.008$	$\alpha_4 = 0.006$	$\alpha_4 = 0.008$
0	1.000000	1.000000	1.000000	1.0000
10	0.941818	0.923131	0.858181	0.8412
20	0.886969	0.852121	0.808181	0.7764
30	0.835252	0.786666	0.761010	0.7167
40	0.786666	0.726161	0.716767	0.6616
50	0.740808	0.670303	0.675050	0.6107
60	0.697777	0.618888	0.635757	0.5638
70	0.657070	0.571212	0.598686	0.5204
80	0.618888	0.527373	0.563838	0.4804
90	0.582727	0.486868	0.530909	0.4435

6 | Result and Discussion

Upon meticulous examination of *Tables 3* and *4*, it becomes apparent that at the juncture of 60 months, the system's reliability and maintainability manifest at 0.4189 and 1.0000, respectively. Concurrently, at this critical interval, subsystems A, B, C, and D showcase analogous reliability metrics, delineated as R(t)= 0.9250, R(t)= 0.7408, R(t)= 0.8353, and R(t)= 0.7320, correspondingly. The probability of achieving satisfactory maintenance and repair within the specified 60-month timeframe is succinctly captured by M(t)= 1.0000 for the holistic system, while the pivotal subsystems exhibit nuanced maintainability indices: M(t)= 0.9999 (A), M(t)= 0.9927 (B), M(t)= 0.9831 (C), and M(t)= 0.9927 (D). Noteworthy is the observation that individual subsystems evince a tendency towards diminishing reliability over the elapsed time, a phenomenon aptly illustrated by *Table 3*, which juxtaposes the reliability of each subsystem against that of the entire system, showcasing a progressive divergence.

Additionally, a salient finding from the analysis underscores the comparative inferiority of subsystem D in terms of reliability when juxtaposed with its counterparts. Hence, the diminished reliability of the overall system over time can be attributed to the lagging reliability performance of subsystem D. Consequently; proactive measures are warranted to bolster the resilience of subsystem D, thereby mitigating the likelihood of failure occurrences and fortifying its reliability, thereby potentially bolstering the system's overall reliability. *Table 4* provides compelling evidence that the maintainability of individual subsystems exhibits an upward trend as time progresses.

Nevertheless, it's noteworthy that the maintainability of each individual subsystem mirrors that of the entire system over time. Crucially, none of the subsystems register inferior maintainability levels. Consequently, any alteration in the maintainability of a subsystem is anticipated to impact the overall maintainability of the system as time elapses. Thus, a strategic blend of offline and online maintenance interventions, meticulously tailored to the system and its subsystems, is imperative to uphold peak performance and sustain the system's operational efficacy. *Tables 5-8* provide a detailed depiction of the dynamic interplay between system reliability and the failure rates of individual subsystems. It becomes apparent from these tables that as time progresses, the overall system reliability experiences a downward trend, a phenomenon commonly observed in complex systems. However, an intriguing insight emerges from the reliability analysis conducted for various failure rate scenarios: system reliability is markedly higher when the failure rates of subsystems are minimized.

This sensitivity analysis underscores the critical role that failure rates play in determining system reliability. Specifically, lower failure rates correspond to higher system reliability, suggesting that mitigating the likelihood of component failures can significantly enhance the overall performance and dependability of the system. Consequently, optimal system reliability can be attained by striving for lower overall failure rates across all subsystems, coupled with the implementation of robust maintenance practices. In light of these findings, it becomes imperative to adopt effective maintenance strategies aimed at reducing failure rates and prolonging the operational lifespan of system components. Regular inspections, proactive maintenance interventions, and the implementation of preventive maintenance schedules emerge as indispensable tools in this endeavor. Additionally, the incorporation of redundant procedures, where feasible, serves as a valuable mechanism for bolstering system reliability by providing alternative pathways to mitigate the impact of component failures.

The insights gleaned from the sensitivity analysis underscore the importance of proactive maintenance and strategic interventions aimed at minimizing failure rates to enhance system reliability. By prioritizing preventive measures and leveraging redundant procedures, stakeholders can optimize the reliability and performance of PV systems for community water supply, thereby ensuring sustainable and uninterrupted access to clean water for communities worldwide. The RAMD analysis technique serves as a powerful tool for a diverse range of stakeholders, including managers, system designers, and engineers, enabling them to conduct comprehensive assessments of system performance and make informed decisions. At the forefront of leveraging RAMD analysis are managers, who wield it as a strategic instrument to govern and optimize reliability parameters such as MTBFs, MTTR, and availability.

Managers play a pivotal role in overseeing the operational efficiency and sustainability of systems, and RAMD analysis equips them with valuable insights into the system's reliability dynamics. By utilizing RAMD analysis at the outer layer, managers can delve into the intricate interplay of reliability metrics and tailor maintenance policies to meet organizational objectives effectively. For instance, by scrutinizing MTBF and MTTR data derived from RAMD analysis, managers can devise maintenance schedules that minimize downtime and maximize system uptime, thereby enhancing operational efficiency and cost-effectiveness. Furthermore, RAMD analysis empowers system designers to optimize system architecture and component selection to meet stringent reliability requirements. By integrating RAMD principles into the design phase, designers can identify potential failure points, select robust components, and incorporate redundancy measures to enhance system resilience and reliability. Engineers also benefit significantly from RAMD analysis, utilizing it as a diagnostic tool to identify performance bottlenecks, troubleshoot system failures, and optimize maintenance strategies. By analyzing RAMD data, engineers can proactively address reliability issues, implement corrective actions, and fine-tune maintenance procedures to ensure optimal system performance. In essence, RAMD analysis serves as a cornerstone for effective decision-making across all levels of system management and engineering. By harnessing the insights derived from RAMD analysis, stakeholders can proactively manage reliability parameters, optimize maintenance practices, and ensure the long-term performance and viability of complex systems.

7 | Conclusion

This study has delved into the intricacies of RAMD analysis to scrutinize the reliability and maintainability of individual components and subsystems within the system. Through a meticulous examination of RAMD measures, including failure rates, repair rates, reliability, and maintainability, we have identified the most sensitive components that significantly impact the overall system performance. The models corresponding to RAMD measures for subsystems were derived and analyzed numerically, ensuring the accuracy and reliability of our findings. Our analysis, as depicted in *Tables 1*, *2*, *5*, and *6*, along with corresponding *Fig. 2* and *Fig. 3*, has shed light on the impact of the rate of failure on panel, inverter, pump, reservoir and system reliability. Notably, our numerical observations underscore a critical insight: the reliability of the entire system is intricately linked to the maintainability of the system. This highlights the pivotal role of maintainability in ensuring sustained system reliability and operational efficiency over time.

Drawing from our findings, we advocate for the adoption of the RAMD approach as a strategic framework to enhance system performance and mitigate the risk of subsystem failures. By implementing proactive maintenance strategies informed by RAMD analysis, stakeholders can preemptively address reliability issues, optimize system operation, and minimize downtime. Additionally, prioritizing the enhancement of subsystem maintainability not only fosters the smooth operation of individual components but also safeguards the integrity of the entire system. In essence, the RAMD approach offers a robust methodology to bolster system resilience, promote operational continuity, and mitigate the adverse effects of component failures. By leveraging the insights gleaned from RAMD analysis, organizations can optimize resource allocation, streamline maintenance practices, and ultimately ensure the sustained performance and reliability of complex systems in diverse operational environments.

Author Contributions

Nazir Isma'il Ibrahim conducted the primary research, including case study observations, interviews, and data analysis. Mansur Hassan and Ibrahim Yusuf contributed to the theoretical framework, methodology design, and result interpretation. Both authors collaborated on writing and revising the manuscript.

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Conflict of Interest

We have no competing interests in this article.

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