Sigma J Eng Nat Sci, Vol. 42, No. 6, pp. 1763−1779, December, 2024

Sigma Journal of Engineering and Natural Sciences
Web page info: https://sigma.yildiz.edu.tr
DOI: 10.14744/sigma.2024.00138

Research Article

Synergistic integration of ram methodology for augmenting reliability and efficiency in solar irrigation systems: a comprehensive study for sustainable rural farming

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ARTICLE INFO

Article history
Received: 27 July 2023
Revised: 22 October 2023
Accepted: 08 January 2024

Keywords:
Solar; Reliability; Availability; Exponentiated Weibull; Irrigation

ABSTRACT

In rural areas around the world, agriculture is a vital source of livelihood and sustenance. However, limited access to electricity and water resources often hampers agricultural productivity, leaving farmers dependent on rainfall or manual labor-intensive irrigation methods. To address this challenge, solar irrigation systems have emerged as a sustainable and efficient solution. However, the existing solar irrigation systems often suffer from reliability issues and suboptimal performance, leading to inefficient water usage, increased maintenance costs, and reduced overall agricultural output. Addressing the reliability and performance optimization challenges of solar irrigation systems for rural farming is essential to ensure sustainable agriculture, increased crop yield, and improved livelihoods for farmers. This study aimed to enhance the performance of solar irrigation systems using reliability, maintainability, availability, and metrics like MTBF and MTTF. The system consists of four subsystems 1, 2, 3, and 4 namely, PV panel, controller, submersible pump, and storage tank sequentially arranged. Subsystem 1 consists of ten (10) units of panels arranged in parallel and connected to subsystem 2 which consists of two (2) unit controllers arranged in parallel, whereas subsystem 3 consists of two (2) units of pumps arranged in parallel and lastly, subsystem 4 comprises of four (4) units of storage tanks arranged in parallel, However, all the four subsystems combined are arranged in series-parallel. For design and prediction, the Markovian birth-death method is employed to assemble the system governing the differential difference equation from the state-to-state transition diagram. The rates of repair and failure of each subsystem are assumed to be exponentiated Weibull distributions and statistically independent. The findings of this research are thought to be valuable for analyzing performance and determining the best solar irrigation system design and feasible preventive and corrective maintenance strategies that may be used in the future to improve system performance, strength, effectiveness, food production output as well and revenue mobilization.

Cite this article as: Yusuf I, Gatawa RI, Isa MS. Synergistic integration of ram methodology for augmenting reliability and efficiency in solar irrigation systems: a comprehensive study for sustainable rural farming. Sigma J Eng Nat Sci 2024;42(6):1763−1779.

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This paper was recommended for publication in revised form by Regional Editor Ahmet Selim Dalkilic

Published by Yıldız Technical University Press, İstanbul, Turkey

INTRODUCTION

A solar irrigation system is a technology that harnesses solar energy to power irrigation processes in agriculture. It provides an eco-friendly and sustainable solution for watering crops and plants using the abundant energy from the sun. The system typically consists of four main components: solar panels, a controller, a submersible pump, and a water distribution system. The solar panels are responsible for capturing sunlight and converting it into electrical energy. This energy is then used to power the pump, which draws water from a water source, such as a well, river, or pond. Solar irrigation systems offer several advantages over traditional irrigation methods. Benefits of solar irrigation systems include renewable and sustainability, reduction in operational cost, increased independence, scalability, environmental benefits, etc. Solar irrigation systems have emerged as a sustainable and efficient solution for agricultural water management. These systems harness the power of solar energy to drive pumps and provide water for irrigation, reducing dependency on conventional energy sources and minimizing environmental impact. To ensure the successful and long-term operation of solar irrigation systems, the principles of reliability, availability, and maintainability play a crucial role. It is worth noting that the efficiency and performance of a solar irrigation system depend on factors such as the available sunlight, the size of the solar array, the water demand, and the irrigation technique used. Proper system design, sizing, and maintenance are crucial to ensure optimal performance and water conservation.

In recent times, a wide range of agricultural technologies have emerged, offering valuable solutions to enhance crop production while minimizing costs and energy consumption. Among these technologies, the crucial aspect of water pumping for irrigation plays a significant role in any crop cultivation method. Traditionally, farmers have relied on either fossil fuel-based systems or grid power to operate their pumps.

Reliability models play a crucial role in enhancing the performance of solar irrigation systems by ensuring their dependability and availability. Reliability, Availability, Maintainability, and Durability (RAMD) are key aspects that need to be considered when designing and operating such systems. RAMD or reliability, availability, and maintainability is a framework used to evaluate the performance of a system. In the case of a solar water irrigation system for rural consumption, RAMD can be used to assess the system's ability to reliably and efficiently provide water for irrigation purposes in rural areas. It is a framework that can be used to evaluate the performance of a solar water irrigation system for rural consumption by assessing its reliability, availability, maintainability, and durability. By using this framework, it is possible to identify any areas of weakness in the system and develop strategies for improving its performance and efficiency. In the context of solar irrigation, reliability encompasses the durability and robustness of various components, such as solar panels, batteries, inverters, pumps, and control systems. A reliable system should be designed, constructed, and maintained in a manner that minimizes the risk of breakdowns, malfunctions, and performance degradation. In the case of solar irrigation, availability relates to the system's capacity to supply water on demand, especially during peak irrigation periods. Factors that affect availability include system design, sizing of components, battery storage capacity, and overall system efficiency. Ensuring high availability involves proper planning, installation, and monitoring of the system to minimize downtime and maximize water supply. Maintainability refers to the ease and effectiveness of conducting maintenance activities on the solar irrigation system. It involves preventive and corrective measures aimed at preserving the system's performance, preventing failures, and extending its operational life. Key aspects of maintainability include regular inspections, cleaning, and maintenance of solar panels, battery maintenance, pump maintenance, and monitoring of system performance. Well-documented maintenance procedures and access to spare parts are essential for efficient and cost-effective system upkeep. The integration of reliability, availability, and maintainability principles in solar irrigation systems is crucial for the sustainable and successful implementation of these systems. A reliable system minimizes the risk of interruptions and breakdowns, ensuring uninterrupted water supply for irrigation. High availability guarantees that the system can meet the demands of agricultural activities, contributing to improved crop yields and water resource management. Effective maintainability practices reduce the costs associated with repairs, optimize system performance, and extend the system's lifespan.

In many rural areas, agriculture heavily relies on irrigation to ensure sufficient crop growth and productivity. However, the existing solar irrigation systems often suffer from reliability issues and suboptimal performance, leading to inefficient water usage, increased maintenance costs, and reduced overall agricultural output. The primary problem is that the current solar irrigation systems deployed in rural farming areas lack the necessary reliability to function consistently and efficiently. Factors such as inadequate system design, substandard components, and improper installation contribute to frequent breakdowns, system failures, and reduced lifespan. These issues result in significant downtime, hampering farmers' ability to irrigate their crops on a regular and reliable basis, leading to reduced yields and financial losses. Moreover, the performance optimization of solar irrigation systems is also a pressing concern. Many existing systems are not designed to maximize water usage efficiency, leading to excessive water wastage and increased energy consumption. Additionally, the suboptimal sizing and configuration of solar panels, batteries, and pumps result in insufficient power generation and storage capacities, hindering the system's ability to meet the irrigation demands of the farms effectively. Addressing the reliability and performance optimization challenges of solar irrigation systems for rural farming is essential to ensure sustainable agriculture, increased crop yield, and improved livelihoods for farmers. A comprehensive approach that encompasses system design improvements, the use of high-quality components, efficient installation and maintenance practices, and intelligent control mechanisms is required to enhance the reliability, performance, and overall effectiveness of solar irrigation systems in rural areas. More sophisticated solar irrigation models with multiple panels and storage tanks should be developed to assist in reducing the risk of a complete breakdown, and operating costs, prolonging the overall reliability, availability, and mean time to failure as well as generating revenue (profit) as well as increase in food production. The reliability and performance optimization of solar irrigation systems for rural farming is a crucial challenge that needs to be addressed.

The paper is organized as follows: Section 2 provides a comprehensive literature review of existing studies, Section 3 describes the system under study, Section 4 discusses the materials and methods employed, Section 5 focuses on the formulation of the RAM models, Section 6 presents the results of numerical simulations and the subsequent discussion of outcomes, and finally, Section 7 concludes the paper, summarizing the main findings and potential avenues for future research.

LITERATURE REVIEW

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. RAMD (reliability, availability, maintainability, and dependability) 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.

Researchers have used a variety of approaches to assess RAMD measures in the literature. To cite a few, [1] investigated the efficiency of the forming industry by assessing system sensitivity analysis. [2] developed Markov models for RAM performance estimation of the circulation system of water. [3] discuss the RAM evaluation of Load Haul Dumpers. [4] were able to compute the RAMD parameters for each component of the system. These parameters provide valuable insights into the criticality and performance of the system's components, aiding in decision-making and optimization efforts. The approach outlined by [5] suggests that the reliability, availability, and maintainability (RAM) of a cement plant can be enhanced by conducting a RAM analysis of its subsystems. This analysis involves utilizing data on the time between failures (TBF) and time to repair (TTR) for all critical subsystems within the plant. [6] discussed the effectiveness of a reciprocating compressor system package installed and used in the oil and gas industries by examining the behavior of each part and component of the reciprocating compressor, which can aid in pinpointing the influence of RAM on the efficiency of the system. [7] used the Markov birth-death process to evaluate the reliability, mean time between failures, and mean time to failure of a series-parallel system. [8] present a methodology for analyzing an industrial system's system performance using uncertain data. The associated membership functions are generated using fuzzy set theory by solving a nonlinear optimization problem with particle swarm optimization. [9] tackled the intricate dynamics of the A-pan crystallization system in a sugar plant by ingeniously integrating mathematical models with a fuzzy reliability approach and Markov birth-death model differential equations. The researchers masterfully derived these complex equations, and to efficiently solve them, they employed the highly accurate Runge-Kutta method of fourth order. [10] embarked on a significant endeavor, addressing the critical aspects of reliability, availability, maintainability, and dependability (RAMD) within the physical processing unit of a sewage treatment plant. To achieve this, the study employed Markovian birth-death processes and derived the essential Chapman-Kolmogorov differential equations, which form the foundation of their analysis. Through this sophisticated mathematical framework, the study was able to ascertain crucial performance measures, including the mean time between failures, mean time to repair, and dependability ratio. [11] undertook a pioneering study aimed at exploring the intricate web of reliability measures within the generator utilized in Sewage Treatment Plants (STP), employing a comprehensive RAMD (Reliability, Availability, Maintainability, and Dependability) approach at the component level. To achieve their objective, the team ingeniously formulated mathematical models based on the Markovian birth-death process, carefully developing models for all subsystems of the generator. [12] Estimate the coliform values of the Tekkekoy deep sea discharge system, which is chosen as an application area, by using a radial-based artificial neural network structure, [13] writes on production-distribution network system for a company, which is active in producing bottled natural spring water was established. [10] made significant strides towards optimizing the operational performance of a soft water treatment and supply plant (SWTS-Plant) by developing comprehensive models for reliability, availability, and maintainability (RAM) measures. Through an illustrative case study centered around the SWTS plant situated in the high-rise society ABC, Jaipur, the researchers meticulously conducted a RAM analysis. This analysis entailed a detailed descriptive examination of the time to failure and repair, accompanied by trend analysis and a rigorous goodness-of-fit test. [14] Defined a Secure Simple Epidemic Algorithm (SSEA) for PSN where a security condition controls the traffic. [15] Classification algorithms were used to classify electromyography and depth sensor data, [16] Optimum

CW size is defined through meta-heuristic optimization algorithms.

[17] conducted a meticulous analysis of the evaporation system within a sugar plant, focusing on the application of reliability, availability, maintainability, and dependability measures. The researchers aimed to identify the most sensitive subsystems in the evaporation process, a critical aspect for optimizing overall performance. To achieve this, they skillfully constructed transition diagrams for all subsystems and expertly derived corresponding Chapman-Kolmogorov differential equations, utilizing the powerful Markov birth-death process. [18] tackled the intricate analysis of a microprocessor system, exploring its reliability, availability, maintainability, and dependability aspects. This microprocessor system was thoughtfully designed with seven essential subsystems, encompassing input, terminal, processor, main memory disk, addressing modes, disk controller, and disk drives. The researchers conducted a rigorous examination of each subsystem's performance in terms of reliability, availability, maintainability, and dependability, aiming to identify potential areas for optimization and enhancement. To facilitate this analysis, the team skillfully crafted state transition diagrams for all subsystems and adeptly derived governing equations using the powerful Markov birth-death process. [19] Focuses on studying the reliability and maintainability of a sugar manufacturing plant by collecting data over six months. The researchers conducted a thorough descriptive statistical analysis on the time to repair and time between failures data. By determining the best-fitted distribution and its parameters, as well as conducting trend and serial correlation analysis, the study aimed to optimize the plant's performance and ensure its efficient operation. [20] Sought to evaluate the reliability, availability, and maintainability of a hot standby database system by examining its failure data. The researchers assessed these aspects using fundamental probability principles and estimated the parameters of established probability distributions. Comprehensive statistical analysis, including trend and serial correlation assessment, was conducted to analyze the reliability and maintainability of both the primary unit and the hot standby unit within the system. [21] Presented a comprehensive framework aimed at evaluating reliability, availability, and maintainability, while also optimizing maintenance practices, to enhance the conveying process of vehicle bodies in an automotive assembly line. The findings from the reliability, availability, and maintainability analysis revealed that the main bottlenecks within the process were associated with the forklift and loading equipment's reliability and maintainability. [22] Conducted a comprehensive study, utilizing data sets from a wine packaging line's production system, with the primary objective of presenting a thorough analysis of reliability, availability, and maintainability (RAM) to provide valuable insights and results for the overall system performance. [23] Successfully devised and applied reliability, availability, and maintainability (RAM) indices to evaluate and enhance the performance of an automated croissant production line under actual operating conditions. Through this comprehensive study, the authors convincingly demonstrate the immense utility of RAM analysis in making informed decisions regarding maintenance intervals and devising an optimal maintenance strategy, ensuring smooth and efficient operations in the production line.

Various studies have been conducted to assess the reliability of agriculture and irrigation machinery. These studies typically involve collecting data on the performance and failure rates of different types of agricultural and irrigation machinery under various operating conditions. The data is then analyzed to determine reliability metrics such as mean time between failures (MTBF), mean time to repair (MTTR), and availability, [24] developed availability models for different types of solar pumps and examined their economic feasibility. Their research indicated that the cost of operating a diesel pump set for irrigation purposes was found to be higher than that of the various types of solar pumps analyzed, [25] conducted an analysis of the socio-economic and climatic implications arising from the implementation of photovoltaic-operated high-efficiency irrigation systems, [19] embarked on a comprehensive RAMD (Reliability, Availability, Maintainability, and Dependability) study focused on the Tube-wells Integrated with Underground Pipelines (TIUP) for irrigation systems. Their research endeavors were centered around conducting an in-depth RAMD analysis, coupled with the integration of Failure Modes and Effects Analysis (FMEA), all unified through the development of an innovative stochastic model utilizing the powerful Markovian approach. The ultimate goal was to accurately estimate the Steady-State Availability (SSA) of the TIUP, ensuring a thorough understanding of its performance under various conditions. [26] Introduce modified Bernstein-type operators based on two real parameters and study their various approximation properties, [27] study a new generalization of the Bernstein operator based on the symmetric range, [28] study a new operator of the modified Jain-Gamma operators which preserves linear function.

The majority of reliability analysis studies concerning irrigation systems tend to concentrate on conventional energy sources such as the electric grid, generators, and tractors. These sources often come with high handling costs and their failure can severely impact the irrigation process. However, there is a noticeable lack of research focusing on the implementation of solar irrigation systems, comprising PV panels, controllers, submersible pumps, and storage tanks, as well as their RAMD (Reliability, Availability, Maintainability, and Dependability) and performance analysis. Understanding the implications of such solar irrigation systems on agricultural production, particularly food items, is a crucial area that requires more attention and investigation in the field of irrigation research.

For this reason, this paper considered a solar water irrigation system consisting of four different subsystems configured as a series-parallel system. The performance of the system is studied using the first-order differential-difference equations. Reliability, availability, maintainability, MTTF, and MBTF are computed as one of the performance measures of system strength and effectiveness for each subsystem. The objectives of this paper are fourfold. The first is to formulate novel models of RAM analysis of solar water irrigation systems. The second is to develop the explicit expressions for the availability, reliability, mean time between failure, maintainability, mean time to failure, and dependability for each subsystem. The third is to see the performance of the system through RAM models under exponentiated Weibull distribution. The fourth is to capture the effect of time, rate of failure, and repair on system reliability, maintainability, and availability.

DESCRIPTION AND NOTATIONS OF THE SYSTEM

Solar irrigation is a sustainable and cost-effective solution that harnesses the power of the sun to provide water for agricultural purposes in rural farming communities. It offers an alternative to traditional irrigation methods that rely on fossil fuels or grid electricity, which may be inaccessible or costly in remote areas. By using solar energy, farmers can reduce their dependence on non-renewable resources and lower their operational costs while ensuring a reliable water supply for their crops. Solar irrigation systems typically consist of photovoltaic (PV) panels, a pump, a water storage tank, and a network of pipes and sprinklers. The PV panels capture sunlight and convert it into electricity, which powers the pump. The pump draws water from a water source, such as a well, river, or pond, and transfers it to the storage tank. From the tank, the water is distributed through the pipes and sprinklers to irrigate the fields. The solar water irrigation system in this study has components:

Notation and Assumptions of the Model Notations

v_1: *stand for failure rate of subsystem* 1
v_2: *stand for failure rate of subsystem* 2
v_3: *stand for failure rate of subsystem* 3
v_4: *stand for failure rate of subsystem* 4
m_1: *stand for repair rate of subsystem* 1
m_2: *stand for repair rate of subsystem* 2
m_3: *stand for repair rate of subsystem* 3
m_4: *stand for repair rate of subsystem* 4

Table 1. System Configuration

Subsystem	Primary unit in operation	Mode of operation
Panels	10	Parallel
Controller	2	Parallel
Pump	2	Parallel
Storage tanks	4	Parallel

Notation and Assumptions of the Model Notations
v_1: *stand for failure rate of subsystem* 1
v_2: *stand for failure rate of subsystem* 2
v_3: *stand for failure rate of subsystem* 3
v_4: *stand for failure rate of subsystem* 4
m_1: *stand for repair rate of subsystem* 1
m_2: *stand for repair rate of subsystem* 2
m_3: *stand for repair rate of subsystem* 3
m_4: *stand for repair rate of subsystem* 4
$P_i(t)$: Stand for Probability that a system is in a certain state at a given time.
A_{Vk}: Stand for at time t, Availability the system

Assumptions

a. Failure of the unit/subsystem is independent of the failure of each other
b. Repair / Replacement is immediate.
c. It is assumed that all the subsystems are active.
d. Each failure is repairable.
e. Rate of failure and repair obeys exponential distribution.

MATERIAL AND METHODS

Reliability Models

The chance that a system/machine will be up and running throughout a period t is defined as reliability. Thus, reliability $R(t) = P_r\{T > t\}$, where T is the time when the system is down and not running with $R(t) \geq 0$, $R(t) = 1$. Thus,

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

and

$$R(t) = 1 - \left(1 - e^{-(\lambda t)^{\gamma}}\right)^{\alpha} \tag{2}$$

for exponentiated Weibull distributed rate of failure respectively.

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

Maintainability

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

where μ is the constant system's repair rate.

Dependability

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

where $d = \frac{\mu}{\theta}$.

MTBF

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

Table 2. Failure and repair rate

Subsystem	Failure rate Operational Units	Repair rate
Panel	$v_1 = 0.004$	$m_1 = 0.4$
Controller	$v_2 = 0.0016$	$m_2 = 0.7$
Pump	$v_3 = 0.005$	$m_3 = 0.8$
Storage tank	$v_4 = 0.012$	$m_4 = 0.75$

$$MTBF = \int_0^{\infty} R(t)\,dt = \int_0^{\infty} e^{-\theta t}\,dt = \frac{1}{\theta}. \tag{6}$$

MTTR

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

$$MTTR = \mu^{-1} \tag{7}$$

where μ is the system's repair rate.

FORMULATION OF RELIABILITY, AVAILABILITY, AND MAINTAINABILITY MODELS FOR SOLAR IRRIGATION SYSTEM

In this section, Chapman Kolmogorov differential equations for each subsystem have been constructed using the Markov birth-death process for the mathematical modeling of solar irrigation systems. Performance metrics such as availability, reliability, maintainability, and dependability have been derived by solving the appropriate Chapman-Kolmogorov differential equations in a steady state and employing normalization conditions simultaneously. Table 2 displays various subsystem failure and repair rates.

RAMD Models for Subsystem 1: The PV Panel

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. From Table 1, the PV panel subsystem has ten panels in active parallel. Through Table 3 below, the Chapman-Kolmogrov differential-difference equations (8)-(18) are derived using the Markovian birth-death process.

Table 3. Transition rate table for Solar Panels

	S_0	S_1	S_2	S_3	…	S_8	S_9	S_{10}
S_0	0	$10v_1$	0	0	…	0	0	0
S_1	m_1	0	$9v_1$	0	…	0	0	0
S_2	0	m_1	0	$8v_1$	…	0	0	0
S_3	0	0	m_1	0	…	0	0	0
	…	…	…	…	…		…	…
S_8	0	0	0	0	…	0	$2v_1$	0
S_9	0	0	0	0	…	m_1	0	v_1
S_{10}	0	0	0	0	…	0	m_1	0

$$\frac{d}{dq}p_0(q) = -10v_1p_0(q) + m_1p_1(q) \tag{8}$$

$$\frac{d}{dq}p_1(q) = -(9v_1 + m_1)p_1(q) + 10v_1p_0(q) + m_1p_2(q) \tag{9}$$

$$\frac{d}{dq}p_2(q) = -(8v_1 + m_1)p_1(q) + 9v_1p_1(q) + m_1p_3(q) \tag{10}$$

$$\frac{d}{dq}p_3(q) = -(7v_1 + m_1)p_3(q) + 8v_2p_0(q) + m_1p_4(q) \tag{11}$$

$$\frac{d}{dq}p_4(q) = -(6v_1 + m_1)p_6(q) + 7v_1p_3(q) + m_1p_5(q) \tag{12}$$

$$\frac{d}{dq}p_5(q) = -(5v_1 + m_1)p_5(q) + 6v_1p_4(q) + m_1p_6(q) \tag{13}$$

$$\frac{d}{dq}p_6(q) = -(4v_1 + m_1)p_6(q) + 5v_1p_5(q) + m_1p_7(q) \tag{14}$$

$$\frac{d}{dq}p_7(q) = -(3v_1 + m_1)p_7(q) + 4v_1p_6(q) + m_1p_8(q) \tag{15}$$

$$\frac{d}{dq}p_8(q) = -(2v_1 + m_1)p_8(q) + 3v_1p_7(q) + m_1p_9(q) \tag{16}$$

$$\frac{d}{dq}p_9(q) = -(v_1 + m_1)p_1(q) + 2v_1p_8(q) + m_1p_{10}(q) \tag{17}$$

$$\frac{d}{dq}p_{10}(q) = -m_1p_{10}(q) + v_1p_9(q) \tag{18}$$

The normalizing condition for this problem is

$$p_0(q) + p_1(q) + p_2(q) + p_3(q) + \ldots + p_9(q) + p_{10}(q) = 1 \tag{19}$$

Availability of PV panel subsystems is

$$A_{V1}(q) = p_0(q) + p_1(q) + p_2(q) + p_3(q) + \ldots + p_9(q) \tag{20}$$

Setting (9) to (19) to zero as $q \to \infty$ in steady state and solving recursively with the aid of (19), the availability of the PV panel subsystem in (20) is now

$$A_{V1}(q) = \frac{1 + 10y_1 + 90y_1^2 + 720y_1^3 + 5040y_1^4 + 30240y_1^5 + 151200y_1^6 + 604800y_1^7 + 1814000y_1^8 + 3628800y_1^9}{1 + 10y_1 + 90y_1^2 + 720y_1^3 + 5040y_1^4 + 30240y_1^5 + 151200y_1^6 + \ldots + 3628800y_1^9 + 3628800y_1^{10}} \tag{21}$$

Where $y_k = \frac{v_k}{m_k}$, $k = 1,2,3,4$

The Corresponding reliability, and maintainability of the PV panel subsystem are

$$R_1(q) = 1 - \left(1 - e^{-(v_1 q)^{\gamma}}\right)^{\alpha} \tag{22}$$

$$M_1(q) = 1 - \exp^{-m_1 q} \tag{23}$$

RAMD Models for Subsystem 2: The Controller

Controllers are also essential components that ensure the efficient and effective operation of the system. They regulate the power output from the solar panels and the submersible pump and monitor the system's performance to ensure that it operates optimally. From Table 1, the controller subsystem has two units in active parallel. Through Table 4 below, the Chapman-Kolmogrov differential-difference equations (24)-(27) are derived using the Markovian birth-death process.

Table 4. Transition rate table for Controller

	S_0	S_1	S_2
S_0	0	$2v_2$	0
S_1	m_2	0	v_2
S_2	0	m_2	0

$$\frac{d}{dq} p_0(q) = -2v_2 p_0(q) + m_2 p_1(q) \tag{24}$$

$$\frac{d}{dq} p_1(q) = -(v_2 + m_2) p_1(q) + 2v_2 p_0(q) + m_2 p_2(q) \tag{25}$$

$$\frac{d}{dq} p_2(q) = -m_2 p_2(q) + v_2 p_1(q) \tag{26}$$

The normalizing condition for this problem is

$$p_0(q) + p_1(q) + p_2(q) = 1 \tag{27}$$

The availability of controller subsystems is

$$A_{V2}(q) = p_0(q) + p_1(q) \tag{28}$$

Setting (25) to (28) to zero as $q \to \infty$ in steady state and solving recursively with the aid of (27), the availability of controller subsystem in (28) is now

$$A_{V2}(q) = \frac{1 + 2y_2}{1 + 2y_2 + 2y_2^2} \tag{29}$$

The Corresponding reliability, and maintainability of the controller subsystem are

$$R_2(q) = 1 - \left(1 - e^{-(v_2 q)^{\gamma}}\right)^{\alpha} \tag{30}$$

$$M_2(q) = 1 - \exp^{-m_2 q} \tag{31}$$

RAMD Models for Subsystem 3: The Submersible Pump

Submersible pumps are responsible for pumping water from the source to the storage tank, and their performance is critical in determining the system's overall efficiency. The type and capacity of the submersible pump used should be carefully selected to ensure that it matches the system's power output and water pumping requirements. From Table 1, the submersible subsystem has two units in active parallel. Through Table 5 below, the Chapman-Kolmogrov differential-difference equations (34)-(34) are derived using the Markovian birth-death process.

Table 5. Transition rate table for Submersible pump

	S_0	S_1	S_2
S_0	0	$2v_3$	0
S_1	m_3	0	v_3
S_2	0	m_3	0

$$\frac{d}{dq} p_0(q) = -2v_3 p_0(q) + m_3 p_1(q) \tag{32}$$

$$\frac{d}{dq} p_1(q) = -(v_3 + m_3) p_1(q) + 2v_3 p_0(q) + m_3 p_2(q) \tag{33}$$

$$\frac{d}{dq} p_2(q) = -m_3 p_2(q) + v_3 p_1(q) \tag{34}$$

The normalizing condition for this problem is

$$p_0(q) + p_1(q) + p_2(q) = 1 \tag{35}$$

The availability of submersible pump subsystems is

$$A_{V3}(q) = p_0(q) + p_1(q) \tag{36}$$

Setting (33) to (35) to zero as $q \to \infty$ in steady state and solving recursively with the aid of (35), the availability of submersible pump subsystem in (36) is now

$$A_{V3}\left(q\right)=\frac{1+2y_3}{1+2y_3+2y_3^2} \tag{37}$$

The Corresponding reliability, and maintainability of the submersible pump subsystem are

$$R_3\left(q\right)=1-\left(1-e^{-\left(v_3 q\right)^{\gamma}}\right)^{\alpha} \tag{38}$$

$$M_3\left(q\right)=1-\exp^{-m_3 q} \tag{39}$$

RAMD Models for Subsystem 4: The Storage Tank

Storage tanks are also crucial components of solar-powered water pumping systems, as they store the water that has been pumped from the source. The size and capacity of the storage tank should be carefully selected to ensure that it meets the water demand of the intended application. A storage tank for reserving water for irrigation is a container used to store water for agricultural purposes. It is typically made of materials that can withstand the weight and pressure of the water being stored, such as concrete, steel, or plastic. The size of the tank will depend on the amount of water needed for irrigation, the frequency of irrigation, and the size of the land being irrigated. The tank can be installed above ground or below ground, depending on the available space and the desired level of visual impact. To ensure the quality of the water, the tank should be designed to prevent contamination from external sources. It should also be equipped with an inlet for filling and an outlet for withdrawing water, as well as appropriate filters and valves. Regular maintenance of the tank is necessary to prevent leaks, ensure structural integrity, and maintain the water quality. This can include periodic cleaning and inspection, as well as repairs and replacements as needed. From Table 1, the storage tank subsystem has four units in active parallel. Through Table 6 below, the Chapman-Kolmogrov differential-difference equations (40)-(44) are derived using the Markovian birth-death process.

Table 6. Transition rate table for Storage Tanks

	S_0	S_1	S_2	S_3	S_4
S_0	0	$4v_4$	0	0	0
S_1	m_4	0	$3v_4$	0	0
S_2	0	m_4	0	$2v_4$	0
S_3	0	0	m_4	0	v_4
S_4	0	0	0	m_4	0

$$\frac{d}{dq}p_0\left(q\right)=-4v_4p_0\left(q\right)+m_4p_1\left(q\right) \tag{40}$$

$$\frac{d}{dq}p_1\left(q\right)=-\left(3v_4+m_4\right)p_1\left(q\right)+4v_4p_0\left(q\right)+m_4p_2\left(q\right) \tag{41}$$

$$\frac{d}{dq}p_2\left(q\right)=-\left(2v_4+m_4\right)p_1\left(q\right)+3v_4p_1\left(q\right)+m_4p_3\left(q\right) \tag{42}$$

$$\frac{d}{dq}p_3\left(q\right)=-\left(v_4+m_4\right)p_3\left(q\right)+2v_4p_2\left(q\right)+m_4p_4\left(q\right) \tag{43}$$

$$\frac{d}{dq}p_4\left(q\right)=-m_4p_4\left(q\right)+v_4p_3\left(q\right) \tag{44}$$

The normalizing condition for this problem is

$$p_0\left(q\right)+p_1\left(q\right)+p_2\left(q\right)+p_3\left(q\right)+p_4\left(q\right)=1 \tag{45}$$

Availability of storage tank subsystems is

$$A_{V4}\left(q\right)=p_0\left(q\right)+p_1\left(q\right)+p_2\left(q\right)+p_3\left(q\right) \tag{46}$$

Setting (40) to (44) to zero as $q\to\infty$ in steady state and solving recursively with the aid of (45), the availability of the storage tank subsystem in (46) is now

$$A_{V4}\left(q\right)=\frac{1+4y_4+12y_4^2+24y_4^3}{1+4y_4+12y_4^2+24y_4^3+24y_4^4} \tag{47}$$

The Corresponding reliability, and maintainability of the PV panel subsystem are

$$R_4\left(q\right)=1-\left(1-e^{-\left(v_4 q\right)^{\gamma}}\right)^{\alpha} \tag{48}$$

$$M_4\left(q\right)=1-\exp^{-m_4 q} \tag{49}$$

RAMD Models for Solar Irrigation System

Since the solar irrigation system is a series-parallel system, then

The system reliability, availability, and maintainability of the entire solar irrigation system are:

$$R_{system}\left(q\right)=R_1\left(q\right)*R_2\left(q\right)*R_3\left(q\right)*R_4\left(q\right) \tag{50}$$

$$A_{V\,system}\left(q\right)=A_{V1}*A_{V2}*A_{V3}*A_{V4} \tag{51}$$

$$M_{system}\left(q\right)=M_1\left(q\right)*M_2\left(q\right)*M_3\left(q\right)*M_4\left(q\right) \tag{52}$$

NUMERICAL SIMULATION AND DISCUSSION

Numerical simulations of reliability, availability, maintainability, and dependability are discussed in this section.

This section presents the numerical simulations to demonstrate how the model's durability, efficacy, and

Table 7. Change in reliability concerning change in the rate of failure of PV panel

q	PV panel				Solar irrigation system			
	$v_1 = 0.002$	$v_1 = 0.003$	$v_1 = 0.004$	$v_1 = 0.005$	$v_1 = 0.002$	$v_1 = 0.003$	$v_1 = 0.004$	$v_1 = 0.005$
0	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
20	0.999937	0.999858	0.999748	0.999608	0.995640	0.995561	0.995452	0.995312
40	0.999748	0.999437	0.999008	0.998463	0.983554	0.983248	0.982825	0.982289
60	0.999437	0.998750	0.997804	0.996609	0.965108	0.964443	0.963530	0.962376
80	0.999008	0.997804	0.996157	0.994089	0.941508	0.940373	0.938820	0.936872
100	0.998463	0.996609	0.994089	0.990944	0.913813	0.912116	0.909810	0.906931

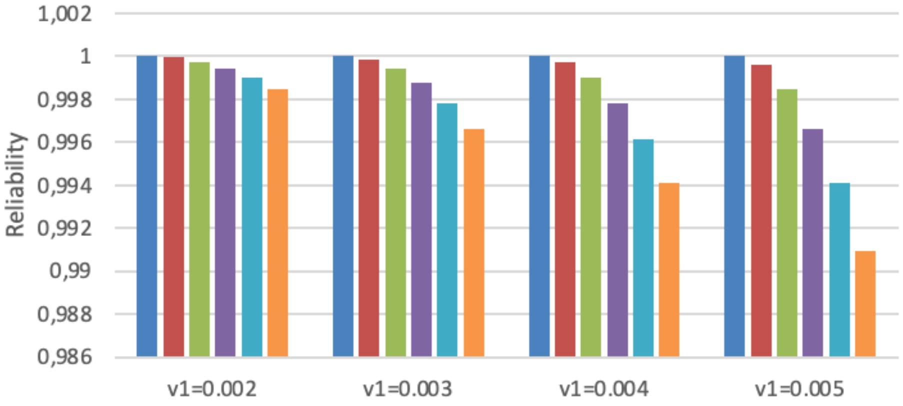

Figure 1. Impact of change v_1 on the reliability of PV panel.

Table 8. Change in reliability concerning change in the rate of failure of the Controller

	Controller				Solar irrigation system			
	$v_2 = 0.0012$	$v_1 = 0.0014$	$v_1 = 0.0016$	$v_1 = 0.0018$	$v_2 = 0.0012$	$v_1 = 0.0014$	$v_1 = 0.0016$	$v_1 = 0.0018$
0	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
20	0.997804	0.997034	0.996156	0.995174	0.997098	0.996328	0.995451	0.994470
40	0.991621	0.988773	0.985564	0.982013	0.988865	0.986025	0.982825	0.979284
60	0.982014	0.976084	0.969482	0.962261	0.975985	0.970091	0.963530	0.956353
80	0.969482	0.959725	0.948988	0.937380	0.959095	0.949443	0.938820	0.927337
100	0.954472	0.940358	0.925005	0.908600	0.938792	0.924910	0.909809	0.893673

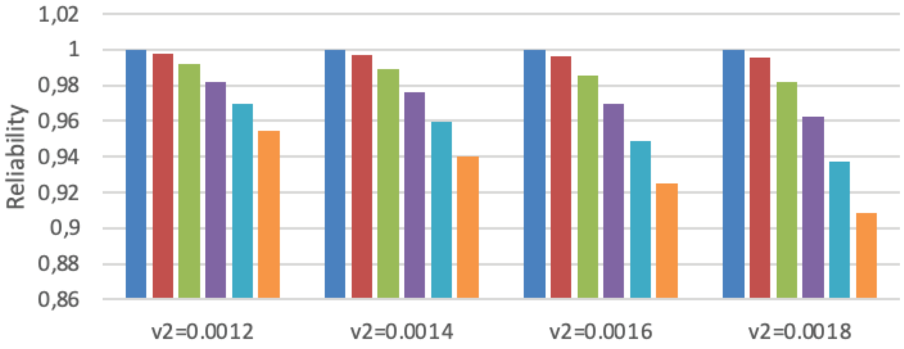

Figure 2. Impact of change v_2 on the reliability of the Controller.

Table 9. Change in reliability concerning change in the rate of failure of Submersible pump

	Submersible pump				**Solar irrigation system**			
	$v_3 = 0.001$	$v_3 = 0.003$	$v_3 = 0.005$	$v_3 = 0.007$	$v_3 = 0.001$	$v_3 = 0.003$	$v_3 = 0.005$	$v_3 = 0.007$
0	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
20	0.999984	0.999857	0.999607	0.999237	0.995826	0.995700	0.995451	0.995083
40	0.999936	0.999437	0.998462	0.997034	0.984276	0.983785	0.982825	0.981419
60	0.999857	0.998749	0.996608	0.993508	0.966671	0.965600	0.963530	0.960533
80	0.999748	0.997803	0.994088	0.988773	0.944165	0.942328	0.938820	0.933800
100	0.999607	0.996608	0.990944	0.982932	0.917764	0.915010	0.909809	0.902454

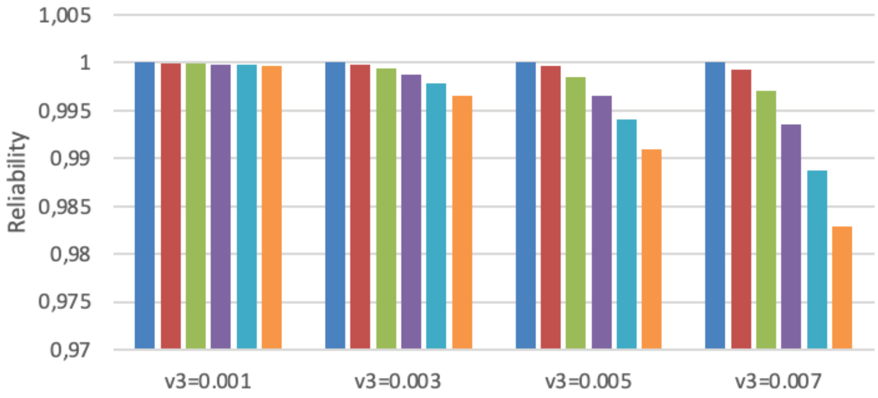

Figure 3. Impact of change v_3 on reliability of Submersible pump Distribution.

Table 10. Change in reliability concerning change in the rate of failure of Storage tank EWD

	Storage tank				**Solar irrigation system**			
	$v_4 = 0.0008$	$v_4 = 0.0012$	$v_4 = 0.0016$	$v_4 = 0.0020$	$v_4 = 0.0008$	$v_4 = 0.0012$	$v_4 = 0.0016$	$v_4 = 0.0020$
0	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
20	0.999989	0.999977	0.999959	0.999936	0.995504	0.995492	0.995474	0.995451
40	0.999959	0.999908	0.999838	0.999748	0.983033	0.982983	0.982914	0.982825
60	0.999908	0.999795	0.999638	0.999437	0.963984	0.963875	0.963723	0.963530
80	0.999838	0.999638	0.999361	0.999008	0.939600	0.939412	0.939152	0.938820
100	0.999748	0.999437	0.999008	0.998462	0.910981	0.910698	0.910306	0.909809

Figure 4. Impact of change v_4 on reliability of Storage tank.

Table 11. Variation in reliability of the system

Time	Reliability of Panel $v_1 = 0.004$	Reliability of Controller $v_2 = 0.016$	Reliability of Pump $v_3 = 0.005$	Reliability of Storage tank $v_4 = 0.002$	System Reliability
0	1.00000	1.00000	1.00000	1.00000	1.00000
20	0.9781385409	0.9961566199	0.9671414601	0.9940889038	0.9367921100
40	0.9250056501	0.9855647895	0.8913111279	0.9781385409	0.7948025741
60	0.8546738976	0.9694823098	0.7964290603	0.9544723303	0.6298697776
80	0.7765475476	0.9489881497	0.6967614102	0.9250056501	0.4749603072
100	0.6967614102	0.9250056501	0.6004235991	0.8913111279	0.3449177600

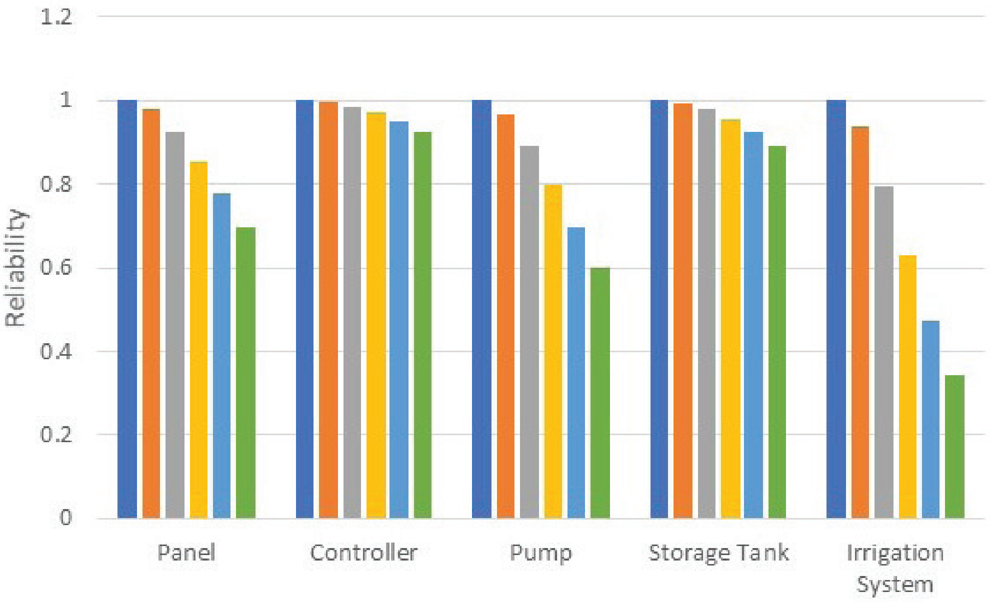

Figure 5. Reliability of various subsystems of solar irrigation system.

Table 12. Change in availability concerning change in the rate of failure of PV panel

v_1 / m_1	Panel subsystem					System				
	0.2	**0.4**	**0.6**	**0.8**	**1.0**	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**
0.01	1.0000	1.0000	1.0000	1.0000	1.0000	0.9921	0.9921	0.9921	0.9921	0.9921
0.02	0.9999	1.0000	1.0000	1.0000	1.0000	0.9920	0.9921	0.9921	0.9921	0.9921
0.03	0.9986	1.0000	1.0000	1.0000	1.0000	0.9907	0.9921	0.9921	0.9921	0.9921
0.04	0.9932	0.9999	1.0000	1.0000	1.0000	0.9853	0.9920	0.9921	0.9921	0.9921
0.05	0.9816	0.9996	1.0000	1.0000	1.0000	0.9739	0.9917	0.9921	0.9921	0.9921

effectiveness have been assessed at various levels. In this case, we use the Lindley and exponentiated Weibull distributions as two alternative distributions to determine the best distribution for improving system reliability, availability, maintainability, and dependability. On this basis, the model's performance is evaluated.

From Table 7-10 and Figures 1-4, it is evident that the reliability of the PV panel, controller, submersible pump, storage tank, and solar irrigation system decreases with time for various combinations of PV panel, controller, submersible pump, and storage tank failure rates. The reliability of the solar irrigation system is consistently lower than that

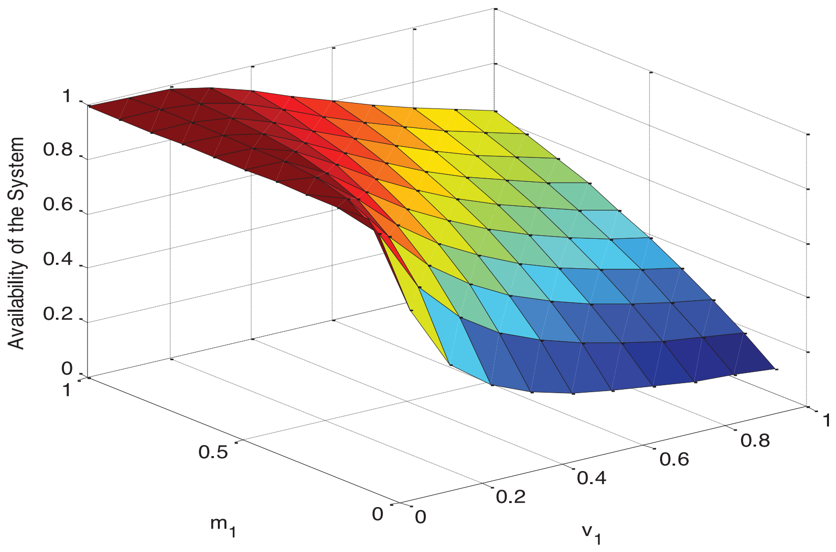

Figure 6. Availability of the system concerning change in v_1 and m_1.

Table 13. Change in availability concerning change in the rate of failure of the Controller

v_2 / m_2	Controller subsystem					System				
	0.2	**0.3**	**0.4**	**0.5**	**0.6**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**
0.01	0.9955	0.9979	0.9988	0.9992	0.9995	0.9885	0.9910	0.9918	0.9923	0.9925
0.03	0.9665	0.9836	0.9903	0.9936	0.9955	0.9598	0.9767	0.9834	0.9867	0.9885
0.05	0.9231	0.9600	0.9756	0.9836	0.9882	0.9166	0.9533	0.9688	0.9767	0.9813
0.07	0.8740	0.9309	0.9566	0.9703	0.9784	0.8679	0.9244	0.9499	0.9635	0.9716
0.09	0.8243	0.8989	0.9347	0.9545	0.9665	0.8185	0.8926	0.9282	0.9479	0.9598

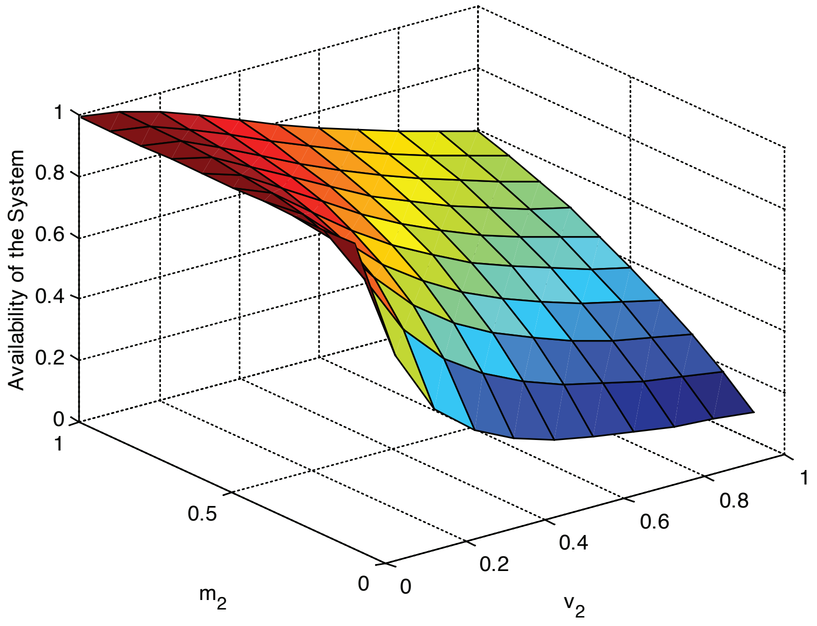

Figure 7. Availability of the system concerning change in v_2 and m_2.

Table 14. Change in availability concerning change in the rate of failure of the Submersible pump

v_3 / m_3	Submersible pump subsystem					System				
	0.1	**0.3**	**0.5**	**0.7**	**0.9**	**0.1**	**0.3**	**0.5**	**0.7**	**0.9**
0.02	0.9459	0.9922	0.9970	0.9985	0.9991	0.9449	0.9911	0.9960	0.9974	0.9980
0.04	0.8491	0.9727	0.9891	0.9942	0.9964	0.8481	0.9716	0.9880	0.9931	0.9953
0.06	0.7534	0.9459	0.9773	0.9876	0.9922	0.7526	0.9449	0.9762	0.9865	0.9911
0.08	0.6701	0.9151	0.9627	0.9792	0.9868	0.6694	0.9141	0.9616	0.9781	0.9857
0.1	0.6000	0.8824	0.9459	0.9692	0.9802	0.5993	0.8814	0.9449	0.9682	0.9791

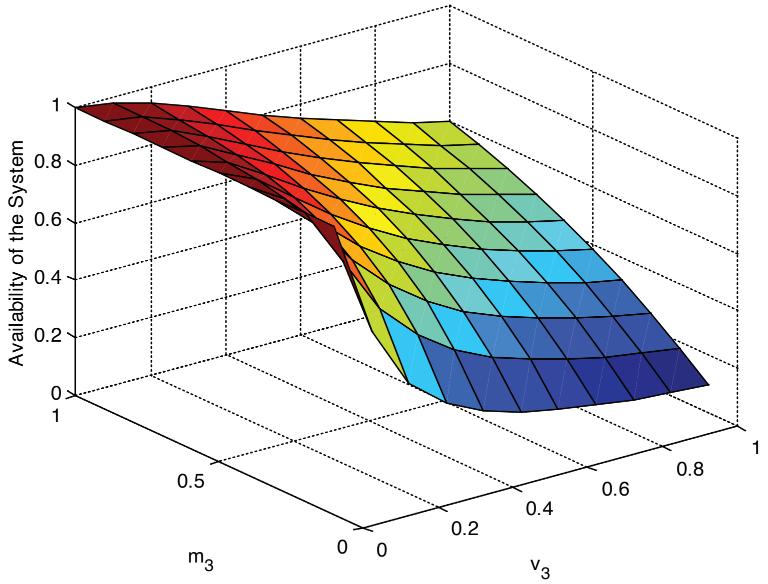

Figure 8. Availability of the system concerning change in v_3 and m_3.

Table 15. Change in availability concerning change in the rate of failure of Storage tank

v_4 / m_4	Storage tank subsystem					System				
	0.4	**0.5**	**0.6**	**0.7**	**0.8**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
0.04	0.9999	0.9993	0.9996	0.9998	0.9999	0.9905	0.9913	0.9917	0.9918	0.9919
0.05	0.9966	0.9984	0.9992	0.9995	0.9997	0.9887	0.9905	0.9912	0.9916	0.9918
0.06	0.9938	0.9971	0.9984	0.9991	0.9994	0.9859	0.9891	0.9905	0.9911	0.9915
0.07	0.9899	0.9951	0.9973	0.9984	0.9990	0.9820	0.9871	0.9894	0.9905	0.9911
0.08	0.9847	0.9924	0.9958	0.9975	0.9984	0.9769	0.9845	0.9879	0.9896	0.9905

of the PV panel, controller, submersible pump, and storage tank subsystems. This implies that the reliability of the solar irrigation system can be enhanced by implementing a careful maintenance strategy. Regular maintenance, inspections, and timely repairs or replacements of faulty PV panels, controllers, submersible pumps, and storage tanks can help mitigate the decline in reliability over time. By ensuring that the PV panels, controller, submersible pump, and storage tank subsystems are in optimal working condition, the overall reliability of the solar irrigation system can be improved. It is important to note that the specific maintenance strategy may vary based on the PV panels, controller, submersible pump and storage tank subsystems failure rates, and other factors. Consulting with experts in the field and following manufacturer guidelines can help develop an effective maintenance plan to enhance the reliability of the solar irrigation system.

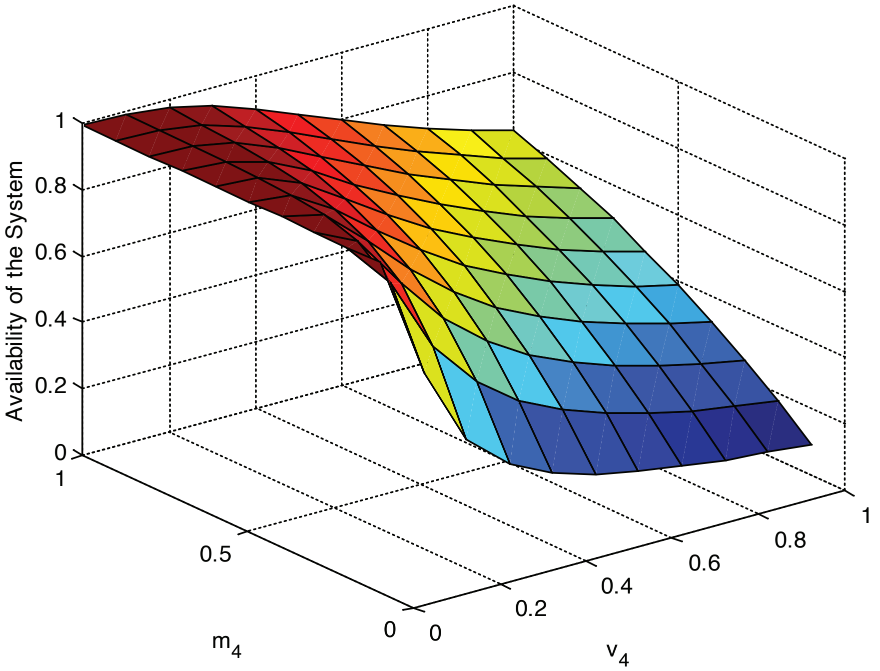

Figure 9. Availability of the system concerning change in v_4 and m_4.

Table 16. Change in maintainability

Time	Maintainability of Panel $m_1 = 0.4$	Maintainability of Controller $m_2 = 0.7$	Maintainability of Pump $m_3 = 0.8$	Maintainability of Storage tank $m_4 = 0.75$	System Maintainability
0	0.00000	0.00000	0.00000	0.00000	0.00000
20	0.99966	0.99999	0.99999	0.99999	0.99966
40	0.99999	1.00000	1.00000	1.00000	0.99999
60	1.00000	1.00000	1.00000	1.00000	1.00000
80	1.00000	1.00000	1.00000	1.00000	1.00000
100	1.00000	1.00000	1.00000	1.00000	1.00000

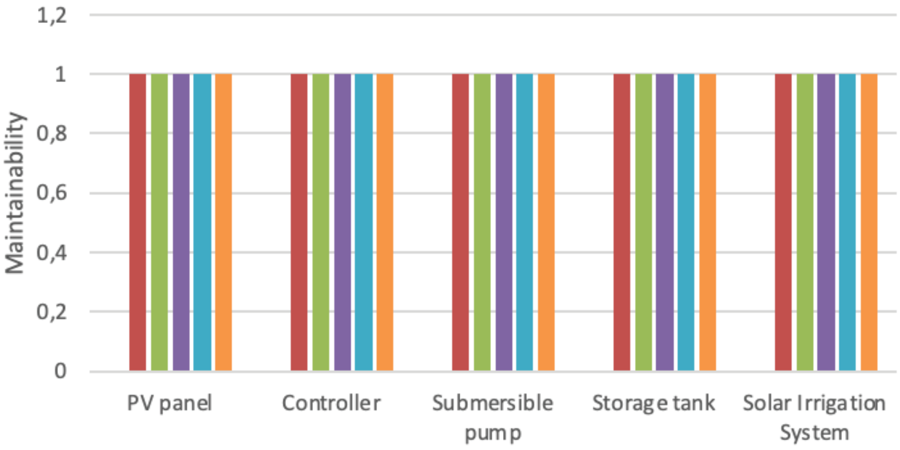

Figure 10. Maintainability of various subsystems of solar irrigation system.

Table 17. RAMD indices

Indices	PV Panel	Controller	Submersible Pump	Storage tank
Reliability	$1-\left(1-e^{-(0.004q)^{0.2}}\right)^2$	$1-\left(1-e^{-(0.0016q)^{0.2}}\right)^2$	$1-\left(1-e^{-(0.005q)^{0.2}}\right)^2$	$1-\left(1-e^{-(0.012q)^{0.2}}\right)^2$
Availability	1.0000	0.9995	0.9991	0.9999
Maintainability	$1-\exp^{-0.40q}$	$1-\exp^{-0.7q}$	$1-\exp^{-0.8q}$	$1-\exp^{-0.75q}$
Dependability	0.9900	0.9977	0.9937	0.9840
MTBF	25	62.5	20	50
MTTR	2.5	1.4286	1.25	1.3333

Figure 6-9 illustrates the relationship between the availability of PV panels, controllers, submersible pumps, storage tanks, and the solar irrigation system. The figures show that as the failure rate v_k, $k = 1,2,3,4$ increases, the reliability of the PV panel decreases. The relationship between failure rate and availability can be inverse. As the failure rate increases, it indicates a higher likelihood of failures occurring within the system. Consequently, the availability of the PV panel, controller, submersible pump, storage tank, and solar irrigation system decreases because there is a greater probability of encountering failures. From this analysis, it can be inferred that the graph in Figure 6-9 demonstrates this inverse relationship between failure rate and availability of PV panels, controllers, submersible pumps, storage tanks, and solar irrigation system reliability. Figure 6-9, presents a surface plot depicting the availability of a solar irrigation system based on the failure rate v_k of the PV panel, controller, submersible pump, and storage tank, and the solar irrigation system and repair rate m_k of the PV panel, controller, submersible pump, storage tank, and the solar irrigation system. According to the figures, as the failure rate v_k of the PV panels, controller, submersible pump, storage tank, and solar irrigation system increases, there is a decrease in the availability of solar irrigation systems. On the other hand, the figure shows that as the repair rate m_k of the PV panel, controller, submersible pump, storage tank, and solar irrigation system increases, there is an increasing pattern in the availability of the solar irrigation system. Based on this information, it can be inferred that reducing the failure rate v_k of the PV panel, controller, submersible pump, storage tank, and solar irrigation system and implementing preventive measures for maintaining the panels will enhance the availability of the solar irrigation system. By minimizing the likelihood of PV panels, controllers, submersible pumps, storage tanks, and solar irrigation system failures and ensuring prompt repairs when necessary, the overall availability of the system can be improved, thereby increasing its reliability and functionality.

Table 12-15 demonstrates the relationship between the failure rate v_k and repair rate m_k of PV panels and the availability of both the PV panel, controller, submersible pump, storage tank, and solar irrigation system. According to the tables, as the failure rate v_k of the PV panel, controller, submersible pump, storage tank, and solar irrigation system increases, both the availability of the PV panel, controller, submersible pump, storage tank and the availability of the solar irrigation system decrease. This suggests that a higher failure rate of the PV panel, controller, submersible pump, and storage tank leads to reduced availability of the entire system. On the other hand, the table shows that the availability of the PV panel, controller, submersible pump, storage tank, and solar irrigation system increases with an increase in the repair rate m_k of the PV panel, controller, submersible pump, storage tank, and solar irrigation system. This implies that a higher repair rate leads to improved availability of the PV panel and the solar irrigation system. From the table, it is clear that the PV panel, controller, submersible pump, storage tank, and solar irrigation system are more reliable and have higher availability compared to the solar irrigation system in the context of the given data.

Table 11 and Figure 5 present the results of the reliability of the PV panel, controller, submersible pump, storage tank, and solar irrigation system. The table and figure show that reliability decreases drastically with time from 0 to 100. From the table and figure it can be seen that the reliability of the solar irrigation system is less than the reliability of the PV panel, controller, submersible pump, and storage tank. The submersible pump has the least reliability among the subsystems from Table 11 and Figure 5 and hence is the most critical subsystem.

Table 16 and Figure 10 present the results of the maintainability of the PV panel, controller, submersible pump, storage tank, and solar irrigation system. The table and figure show that maintainability increases very fast with time from 0 to 100 for different repair rates. From the table and figure it can be seen that the maintainability of the solar irrigation system equally increases as the maintainability of the PV panel, controller, submersible pump, and storage tank increases.

CONCLUSION

RAMD analysis for PV solar irrigation systems is crucial for evaluating reliability, availability, maintainability, and dependability aspects. It enables efficient system design, optimal maintenance planning, enhanced system performance, and cost-effective operation, ultimately contributing to the success and sustainability of such systems. Reliability analysis in RAM for PV solar irrigation systems is essential for ensuring consistent and dependable operation. By evaluating system performance, reducing downtime, optimizing costs, enhancing system longevity, mitigating risks, optimizing energy usage, and supporting decision-making, reliability analysis helps small-scale farmers achieve efficient and sustainable irrigation for their agricultural activities. By conducting reliability and performance analyses, solar irrigation system operators and designers can ensure the system's long-term reliability, maximize its efficiency, and minimize potential downtime. These analyses contribute to the overall sustainability and economic viability of solar irrigation, helping farmers achieve more efficient water management and increased crop yields while reducing reliance on fossil fuels and minimizing environmental impacts. Implementing these reliability models for a solar irrigation system allows you to identify potential failure modes, assess critical components, optimize maintenance activities, and analyze system behavior. By leveraging RAM principles and these reliability models, you can enhance the performance of the solar irrigation system, maximize its availability, and ensure sustainable and reliable operation. In conclusion, the reliability, availability, and maintainability of solar irrigation systems are essential considerations for their successful deployment and long-term operation. By ensuring the reliability of components, maximizing system availability, and implementing efficient maintenance practices, solar irrigation systems can offer sustainable and reliable water supply for agricultural purposes, contributing to increased food production and environmental sustainability.

Reliability, availability, and maintainability analysis is crucial for PV solar irrigation systems to ensure their optimal performance, longevity, and cost-effectiveness. Here are the key reasons for conducting RAM analysis in this context:

1. Reliability Assessment: RAM analysis helps evaluate the reliability of a PV solar irrigation system by assessing the probability of failure or breakdown. By identifying potential failure points and their impact on system operation, reliability analysis aids in designing robust and dependable systems that can withstand various operational conditions and environmental factors.
2. Availability Evaluation: PV solar irrigation systems need to be available for operation during specific periods, typically corresponding to sunlight hours for optimal power generation. RAM analysis helps determine the availability of the system, taking into account factors such as system downtime, maintenance activities, and component failures. This information aids in scheduling maintenance activities and ensuring maximum system availability during critical periods.
3. Maintainability Planning: PV solar irrigation systems require regular maintenance and servicing to sustain their performance and longevity. RAM analysis provides insights into the maintainability aspects of the system, including the mean time to repair (MTTR) and the mean time between failures (MTBF). These metrics assist in planning maintenance activities, estimating downtime for repairs, and optimizing maintenance schedules to minimize disruptions and maximize system uptime.
4. Durability Assessment: The durability of PV solar irrigation systems is vital for their long-term operation and economic viability. RAM analysis evaluates the durability of system components by considering factors such as environmental conditions, material degradation, and wear and tear over time. Understanding the expected lifespan and failure modes of different components allows for informed decision-making regarding system design, component selection, and replacement strategies.
5. Cost Optimization: RAM analysis helps in identifying potential cost-saving opportunities for PV solar irrigation systems. By assessing reliability, availability, and maintainability factors, it becomes possible to optimize maintenance schedules, predict component lifetimes, and minimize operational disruptions. This leads to reduced downtime, lower maintenance costs, and improved overall system performance, resulting in long-term cost savings.

Therefore, RAM analysis for PV solar irrigation systems is crucial for evaluating reliability, availability, maintainability, and durability aspects. It enables efficient system design, optimal maintenance planning, enhanced system performance, and cost-effective operation, ultimately contributing to the success and sustainability of such systems.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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