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MARKOV MODEL ANALYSIS OF SYSTEM RELIABILITY AND SAFETY OF ELECTRONIC SYSTEMS

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ABSTRACT:

The unexpected interruption of electronic systems is one of the most frequently occurring concerns, which may be related to safety issues and long durations of inactivity. This research focuses on evaluating the reliability and robustness of an elementary signal processing circuit, consisting of a capacitor, an NPN transistor, a resistor, and a diode, at an early stage of its design lifecycle. To fulfill this purpose, a continuous-time Markov model was developed, where a graphical representation of all possible states of the system, i.e., a transition diagram with 16 states, and mathematical equations were developed to calculate the overall failure rate and mean time between failures (MTBF) for the operational tenure of the system prior to failure.

Using failure rate data from a reputable source, i.e., the Military Reliability Handbook, four different component "Type" configurations within the circuit were evaluated. It was found that the Type 2 configuration performed better, with the lowest overall failure rate of 3.3675 x 10^{-4} per hour and the highest MTBF of about 2,970 hours, exceeding all other tested configurations. Thus, overall, this study concludes that Markov-based predictive modeling can be an effective tool to identify the most reliable combinations of components, helping designers make better-informed decisions and avoiding failures, which may lead to significant economic losses.

Keywords*: Failure rate, Repair rate, Mean Time Between Failures (MTBF), Markov model, Reliability analysis.*

INTRODUCTION

System reliability and safety analysis is an integral part of electronic system design, especially considering the increasing level of intricacy in electronic systems used in safety-critical applications. In the context of electronic system design, there is an increasing need to analyze the reliability of electronic systems in terms of predicting possible failure scenarios that could result in catastrophic consequences in safety-critical applications. Markov modeling techniques have been identified as effective mathematical tools for modeling the behavior of electronic systems that can exhibit diverse operational states over time. There are many reliability problems that electronic systems face in terms of component degradation, random failures, common cause failure, cascading failure, etc. The conventional techniques used for reliability modeling, like Fault Tree Analysis (FTA) and Reliability Block Diagrams (RBD), offer static modeling techniques but are often found to be inadequate in addressing the dynamic behavior of complex electronic systems, especially in the context of system redundancy, fault tolerance, and sophisticated maintenance strategies. The conventional techniques used for reliability modeling include extensions of FTA and RBD, Petri nets, and Monte Carlo simulations. These methods have some advantages but often do not capture state-dependent behavior or temporal dependencies adequately. Markov models are appropriate for modeling systems that exhibit the Markov property, in which future states depend only on the current state and not on any sequence of previous events. The Markov property allows complex system behaviors to be represented in concise mathematical terms using state transition diagrams and the resulting differential equations. [1] suggested using a Markov model for estimating the reliability of Internet of Things (IoT) devices. This model takes into consideration the various states in which the IoT devices might operate, such as normal, degraded, or failed modes. This model also considers the influence of various factors like temperature, humidity, aging, and failure rate on the reliability of the system. This model was applied to a group of IoT sensors, and the reliability metrics like mean time to failure and probability of system availability were calculated. However, the model used in this paper is a simplistic one, with fewer states and assumptions like a constant rate for transition from one state to another. This might not accurately represent the behavior of IoT devices in real-life scenarios, considering their degradation characteristics. This model primarily focuses on hardware failures and does not take into consideration other important aspects like software failures, connectivity issues, or security concerns in IoT devices. Moreover, the model is not validated with real-life failure rates, and the influence of changing environmental conditions or the presence of a backup system is not considered, which might limit its usage in real-life scenarios, especially for large-scale IoT systems. In another related study, the authors [2] propose an alternative methodology for determining the dependability of electronic control systems. This methodology makes use of a "Hidden Markov Model" (HMM) that can detect a decline in the dependability of the system, even when such a decline is latent. This means that the methodology can detect problems that are not easily observable. It is worth noting that the main aim of this study is to develop a methodology that can track the decline in the dependability of electronic control systems. One of the main findings of this study is that the proposed methodology can track the decline in the dependability of electronic control systems with a reasonable degree of accuracy. However, there is a major limitation associated with this methodology. This limitation is the fact that the methodology is based on a certain number of "hidden health states." In addition, the accuracy of this methodology is highly dependent on the availability of adequate training data. If the initial assumptions regarding the state are wrong, the accuracy of the methodology may be compromised. To address these challenges, the researchers suggest further enhanced Markov modeling techniques specifically designed for electronic system reliability and safety analysis. The researchers propose innovative state reduction techniques to address the problem of sustained failures of electronic/electrical systems by calculating the total failure rate of the signal-generating circuit and its mean time to failure while ensuring the accuracy of the predictions. Furthermore, the researchers suggest the use of phase-type distributions to improve the accuracy of non-exponential transition time approximations, thus making Markov modeling more applicable to real-world problems. In addition, the researchers explore the possibility of incorporating uncertainty quantification techniques to deal with parameter uncertainties of transition rates (which are extracted from various military data handbooks related to reliability). The researchers hope to improve the accuracy of Markov modeling techniques to offer better predictions for electronic system designers and engineers to improve the reliability and safety of complex electronic systems for various applications.

LITERATURE REVIEW OF SOME RELATED WORK

Reliability analysis of electronic systems plays a pivotal role in the contemporary technologically driven world, as discussed in references [3] and [4]. Electronic systems, including communication systems, transportation systems, healthcare systems, and industrial control systems, are integral to the present world. Hence, reliability and availability of such systems are crucial to ensure the smooth operation of the systems, minimizing the downtime, and ensuring the safety of the users, as discussed in reference [5]. Conventionally, reliability analysis of electronic systems has been performed using statistical techniques, as discussed in reference [6] [7]. However, with the increase in the complexity of the systems, there is a need for more sophisticated analysis techniques, as discussed in reference [8]. Markov modeling has been recognized as one of the most powerful techniques for the reliability analysis of electronic systems.

Recently, new state space reduction techniques for the analysis of Markov models have been developed, which can efficiently analyze the reliability of complex electronic systems, as discussed in references [9] and [10]. Additionally, the models can handle multiple failure modes and time-dependent failure rates, which can improve the reliability analysis, as discussed in reference [11]. Hybrid models, including the integration of Markov processes and Bayesian networks, can also be employed to improve the reliability analysis. Real-time reliability analysis can also be performed using the frameworks, as discussed in references [12] and [13]. The integration of stochastic techniques and Markov chains leads to the development of thorough representations of the system [14]. The use of advanced techniques for rare events, computations, and environmental factors improves accuracy. The application of these techniques to new technologies and the development of better decision-making tools demonstrate the advantages of these techniques over conventional techniques [15][16].

Markov modeling has its basis in the mathematical theory of Markov processes and provides a systematic and rigorous approach to the investigation of the dynamic behavior of systems that change over time [17]. Markov modeling has been found to be particularly appropriate for electronic systems owing to its ability to deal with the probabilistic nature of component failures and repairs [18]. By employing Markov modeling techniques,

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researchers and engineers are able to gain important insights into the reliability of electronic systems [20]. The Markov model provides the ability to analyze the system's availability, failure rates, and repair times, among other important factors that affect the performance of the system.

There are various research studies that have successfully applied Markov modeling in assessing the reliability of electronic systems [21]. For example, a Markov model has been applied in assessing the reliability of a power system in a smart grid environment, considering various system failures and repairs [22]. The results of this research study have successfully shown that Markov modeling can be applied in forecasting system reliability and identifying areas that require attention. Another research study applied a Markov model in assessing the reliability of a wireless sensor network in a harsh environment [23],[24], considering failures and repairs of nodes and various types of errors in wireless communication [25],[26]. Furthermore, Markov modeling has been applied in assessing the reliability of electronic systems in various industries where system reliability is of utmost importance. For example, in the aerospace industry, Markov modeling has been applied in assessing the reliability of avionic systems, considering failures and repairs of various system components [27], [28].

Thus, in conclusion, electronic systems are complex and require complex analysis techniques in assessing system reliability. Markov modeling is a robust approach to analyzing electronic systems and assessing their reliability characteristics. The use of Markov models has provided researchers and engineers with insights into system reliability, enabling informed decision-making in enhancing system reliability [29],[30]. In this research, a Markov model is employed to tackle the incessant failure of electronic systems after manufacture or during usage, a reliability assessment technique that can deduce the sensitivity of total system failure rate to variations in its components' failure rates and repair rates.

Furthermore, this paper presents a more flexible and realistic model to determine the total failure rate of an electronic circuit. Here, the Markov modeling of signal processing circuit made up of capacitor, transistor, resistor and diode, generate steady state Markov transition equations for all the states involved in the process, compute the total (overall) failure rate of the circuit and then analyze the results obtained. The model predicts the reliability of those components accurately and successfully. The subsequent sections of this research paper will delve into the methodology, results, and discussions related to the Markov modeling of electronic systems.

METHOD USED

In this paper, a Mathematical framework was used to model randomly changing in the operating conditions of the constituent components (that is diode, capacitor, resistor and transistors) that made up of a signal processing circuit, where future states of each of these components depends only on the current state and not on the sequence of states that preceded it. Hence the detailed method used in this research are exhaustively explained in the sub-section A.

A. System Modeling of Signal Processing Circuit

State space modeling of this circuit was meticulously carried out through the following procedures highlighted in sub-sub section I to sub-subsection V.

Design of Signal Processing Circuit

The circuit used to develop Markov model for this research is given in Figure 1. In this work, a four-component circuit unit as shown Figure 1, was utilized as a case study to illustrate the process of Markov modeling processes. The circuit model represents a signal processing circuit composed of a capacitor C, NPN transistor T, resistor R, and diode D. Each component serves a specific function within the circuit. The capacitor played a crucial role in filtering out ripples from the input signal and determining the voltage that drives the NPN transistor. By smoothing out the signal, the capacitor ensured a more stable and reliable input for further processing. The resistor, on the other hand, restricts the amount of electrical current passing through the circuit. The function of this circuit was to act as a current limiter to restrict the current within a specified range. The diode, being a one-way channel for the flow of electric current, allows the current to flow in one direction. The parallel connection of the diode with the resistor regulates the current supplied to the ground through the terminal 'c'. This circuit ensures that the NPN transistor receives the correct amount of current to produce the desired amplified output signal.

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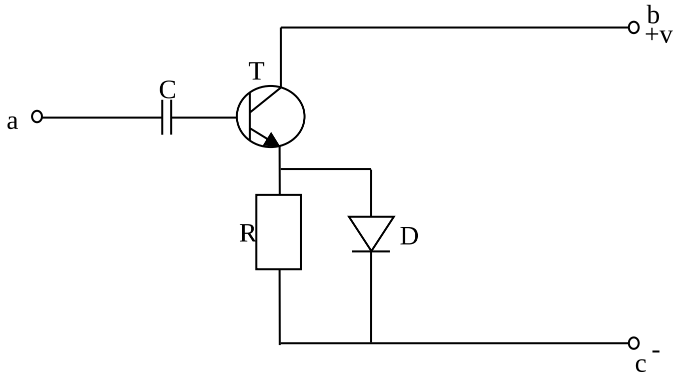

Figure 1: Signal Processing Circuit

The NPN transistor is chosen for the amplification process. The input signal is applied across terminals 'a' and 'c'. As a result, the current from the emitter of the transistor flows through the resistor and diode. Importantly, the current passing through the diode helps to redirect or sink back the current to the NPN transistor, contributing to the generation of the desired output signal. Lastly, the current passing through the resistor is permitted to flow to the ground through terminal 'c'.

II) Maintenance Strategies adopted for the Signal Processing Circuit

In order to effectively repair the components of the circuit, it was essential to consider the schematic block diagram representing the arrangement of these components. The diagram of Figure 2 provided a visual representation of the circuit's components and their connections. The capacitor was represented by block C, and it was connected in series with block T that represented, the NPN transistor. These two blocks were further connected in series with the parallel combination of block R (represented as the resistor) and block D (represented as the diode). For the circuit to operate properly, there was need to take into consideration these three possible scenarios:

(a) All units (blocks) C, T, R, and D were functioning well, indicating that the capacitor, transistor, resistor, and diode respectively were all in good operating conditions.
(b) Only units C, T, and R were functioning well, while block D (diode) had failed. This scenario resulted in a low amplified output signal.
(c) Only units C, T, and D were functioning well, while block R (resistor) had failed. In this case, current flowed to the ground without regulation.

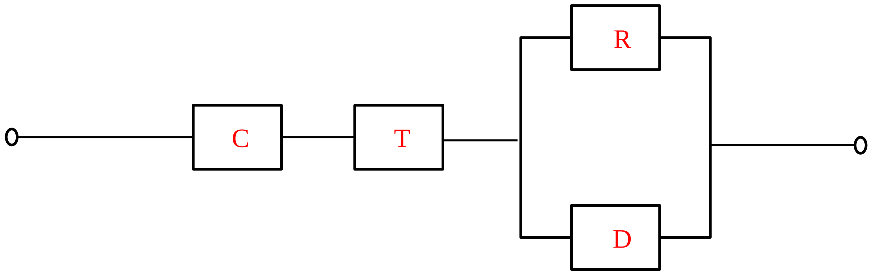

Figure 2: Schematic Block Diagram of Circuit Model

The periodic inspection of this circuit's state, was conducted every *t* hours, assumes an effective repair rate greater than 2/t, where "t" represents the inspection time. Note that the components used in this study were assumed repairable although, in reality, they might not be. The assumption had allowed for a common repair rate expression of 2*t* to be used for all the circuit's components in this paper.

Avoiding the total failure of the circuit which could be caused from the failure of either the capacitor the transistor or both simultaneously, it was necessary to have shorter inspection time's *t* for the capacitor and transistor in comparison to those of the resistor and diode. Therefore, the inspection time for the transistor and capacitor in this work was assumed to be after 500 hours of operations, while the inspection time for the resistor and diode was given as 1000 hours of operations. All the assumptions and considerations provide the necessary guidelines for the inspection and repair of the components in the circuit, ensuring timely maintenance of the overall electronic system.

III. Assumptions made for the Circuit Model Development

The development of the Markov model for the signal processing circuit was based on several assumptions, which were summarized here.

i. It was assumed that each of the transition processes in this circuit, whether it involves a failure events or repair event, had a constant failure rate and a constant repair rate.
ii. The future states of the circuit were assumed to be independent of all past states, except the immediate preceding one.
iii. In each state of this circuit, only one event (either a component failure or repair) could occurred, leading to a transition to another state.
iv. To restore the circuit to its original state where all four components were all in good operating conditions, it was assumed that all the four components needed to undergo repairs at the same time.
v. All components within this circuit were assumed repairable.
vi. It was assumed that there were no common-mode failures in the circuit. Common-mode failures refer to situations where multiple components fail simultaneously or are affected by the same underlying cause.

These assumptions provided a basis for constructing a Markov model that represented the behaviour of the signal processing circuit and facilitated carrying out the desired reliability analysis and performance evaluation of this circuit.

IV) Development of Markov Transition States for the Signal Processing Circuit

Every repairable component within the circuit possesses two states: a good (working) condition and a failed condition, indicating that each component was either in good operating condition or in faulty/damaged operating condition. Repairing a faulty component returns it to ‘as good as new’ operating condition. To effectively represent the operational states of these components, a binary digit coding scheme was adopted. Specifically, a binary digit '1' denoted the failed condition of a component, while '0' represented its good condition. Since the circuit comprises four components, a four-digit binary code was used to describe the various operating conditions of these components in a given state.

In the context of Markov modeling technique, if there are N components in a circuit or system, the total number of generated Markov transition states is 2^N where N is the total number of components in the circuit [31],[32],[33]. Consequently, in this case study, there are 16 possible transition states, corresponding to the $2^4 = 16$. The combinations of these four binary digits to depict the operating conditions of these 16 states were elaborated here.

State S_0 denoted the initial state, where all four components were in good operating conditions, represented as the binary digit combination 0000. State S_1 represents the scenario where only the diode D, had failed and this was represented by binary digit combination 0001. Similarly, state S_{13} depicted the binary digit combination 1100, which signified the good operating conditions of the capacitor and transistor, and the failed operating conditions of the resistor and diode. Notably, state S_1 corresponded to the binary digits combination 0001, while states S_2, S_4, and S_8 corresponded to the binary digit combinations 0010, 0100, and 1000, respectively. These states indicated the failure of the resistor R, transistor T, and capacitor C, respectively.

Table 1: Transition States Analyzed Based on the Number of Failed Components

k = 0	k = 1	k = 2	k = 3	k = 4
S_0	S_1	S_3	S_7	S_{15}
	S_2	S_5	S_{11}	
	S_4	S_6	S_{13}	
	S_8	S_9	S_{14}	

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S_{10}

S_{12}

k = the number of components that had failed

Furthermore, states S_3, S_5, S_6, S_9, S_{10}, and S_{12}, with binary digit combinations 0011, 0110, 1001, 1001, 1010, and 1100 respectively, represented scenarios where two components had failed. Thus, by categorizing the transition states based on the number of failed components, Table 1 was used to depict clearly the various states the circuit could exist. The transition states were visually represented as bubbles, each displaying a four-digit binary combination, allowing for seamless transitions among the states. This representation was depicted in Figure 3.

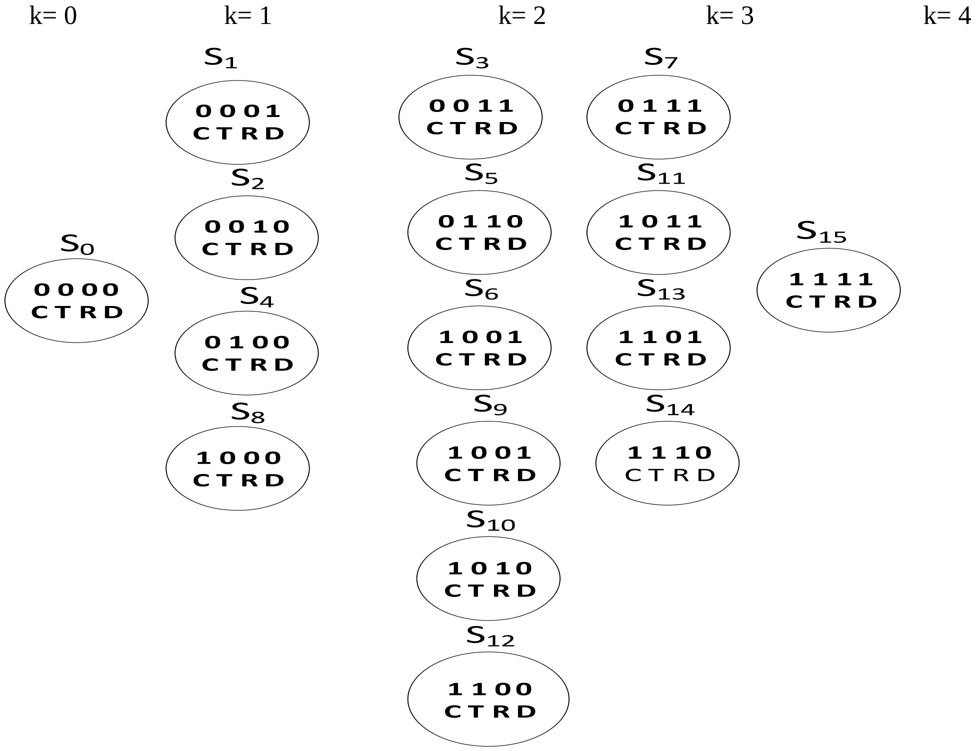

Figure 3. Categorization and arrangement of transition states.

Now, Table 2 shows how transitions took place among these states.

Table 2: Transition State of the Signal Processing Circuit

R,D / C,T	00	01	11	10
00	S_0	S_1	S_3	S_2
01	S_4	S_5	S_7	S_6
11	S_{12}	S_{13}	S_{15}	S_{14}
10	S_8	S_9	S_{11}	S_{10}

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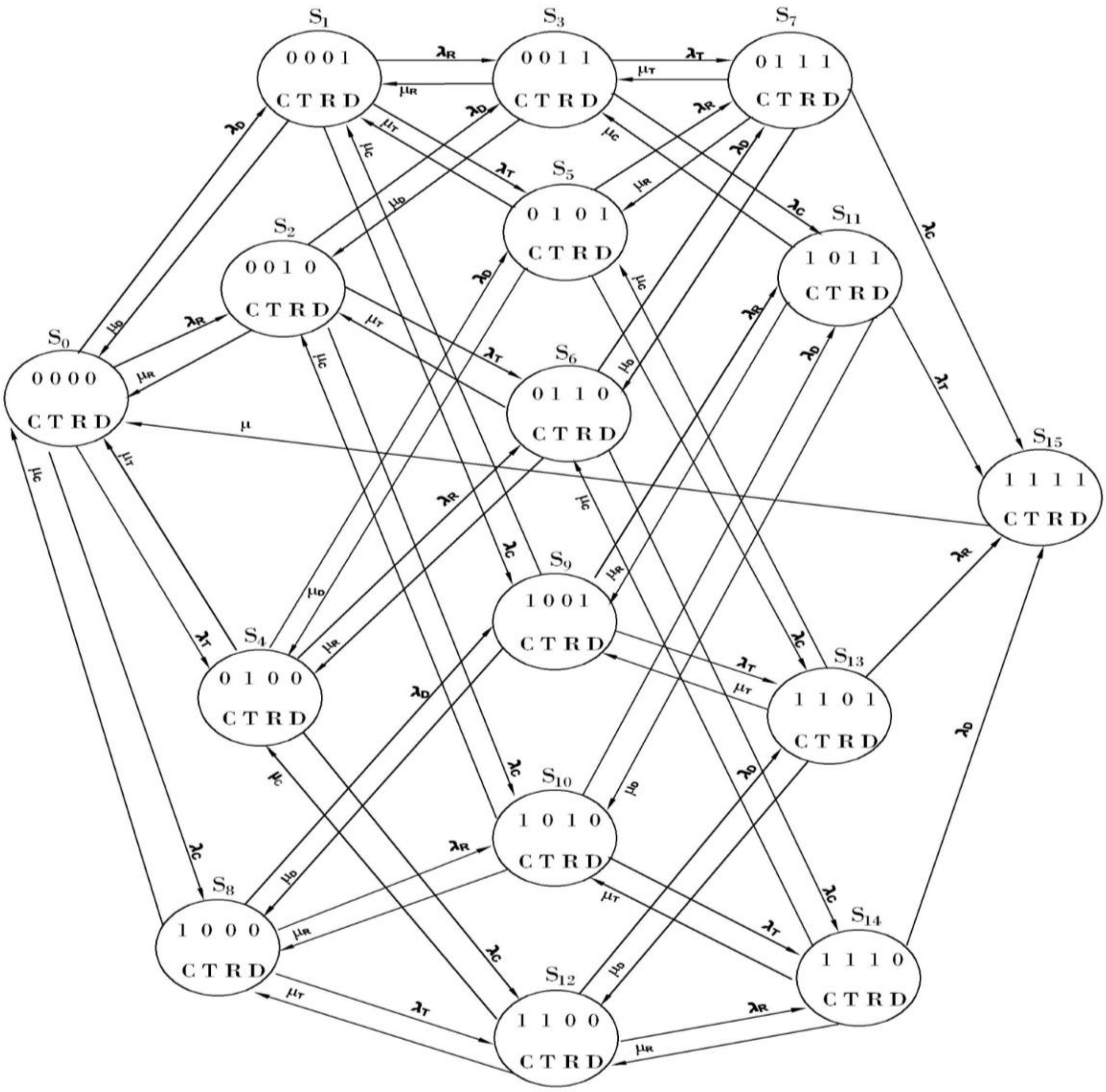

Figure 4. Markov Transition State Diagram of a Signal Processing Circuit.

Upon examining the adjacent sides of each state in Table 2, it became evident that state S_0 allowed transitions to states S_1, S_2, S_4, and S_8. Similarly, state S_{13} permits transitions to states S_5, S_9, S_{12}, and S_{15}. Based on these observations, it is apparent from Table 2 and the transition state diagram that no transitions occur among states S_1, S_2, S_4, and S_8 (where only one component had failed), nor among states S_3, S_5, S_6, S_9, S_{10}, and S_{12}. Transitions from states S_7, S_{11}, S_{13}, and S_{14} resulted into complete circuit failure 1111 (S_{15}), where all four components had failed. The circuit had to be repaired to restore it to state S_0 (0000), in which all four components were in good operating condition. However, it is important to note that repairing the four components of the circuit individually in state S_{15} does not restore the circuit back to states S_7, S_{11}, S_{13}, and S_{14}, as depicted in Figure 4 based on the given assumptions. The repair rate for the capacitor, transistor, resistor, and diode were denoted as μ_C, μ_T, μ_R, μ_D and failure rate for the capacitor, transistor, resistor, and diode were denoted as λ_C, λ_T, λ_R, λ_D, respectively.

V) Development of Transition State Equations from Markov Transition State Diagram

Let P_i be the probability of being in state S_i, where $i = 0$ to 15. The probability at total system failure state, S_{15} is zero, i.e. $P_{15} = 0$. Examining the steady-state equations for these states, it was observed that the rate of transition out of a state is equal to the rate of transition into that particular state. The Markov transition state equations from Figure 4 were derived accordingly, as illustrated below.

S/No	State (S)	Equations
1	S_1	$\lambda_D P_o - K_0 P_1 + \mu_R P_3 + \mu_T P_5 + \mu_C P_9 = 0$
2	S_2	$\lambda_R P_o - K_1 P_2 + \mu_D P_3 + \mu_T P_6 + \mu_C P_{10} = 0$
3	S_3	$\lambda_R P_1 + \lambda_D P_2 - K_4 P_3 + \mu_T P_7 + \mu_C P_{11} = 0$
4	S_4	$\lambda_T P_o - K_2 P_4 + \mu_D P_5 + \mu_R P_6 + \mu_C P_{12} = 0$
5	S_5	$\lambda_T P_1 + \lambda_D P_4 - K_5 P_5 + \mu_R P_7 + \mu_C P_{13} = 0$
6	S_6	$\lambda_T P_2 + \lambda_R P_4 - K_6 P_6 + \mu_D P_7 + \mu_C P_{14} = 0$
7	S_7	$\lambda_T P_3 + \lambda_R P_5 + \lambda_D P_6 - K_{10} P_7 = 0$
8	S_8	$\lambda_C P_o - K_3 P_8 + \mu_D P_9 + \mu_R P_{10} + \mu_T P_{12} = 0$
9	S_9	$\lambda_C P_1 + \lambda_D P_8 - K_7 P_9 + \mu_R P_{11} + \mu_T P_{13} = 0$
10	S_{10}	$\lambda_C P_2 + \lambda_R P_8 - K_8 P_{10} + \mu_D P_{11} + \mu_T P_{14} = 0$
11	S_{11}	$\lambda_C P_3 + \lambda_R P_9 + \lambda_D P_{10} - K_{11} P_{11} = 0$
12	S_{12}	$\lambda_C P_4 + \lambda_T P_{8-} - K_9 P_{12} + \mu_D P_{13} + \mu_R P_{14} = 0$
13	S_{13}	$\lambda_C P_5 + \lambda_T P_9 + \lambda_D P_{12} - K_{12} P_{13} = 0$
14	S_{14}	$\lambda_C P_6 + \lambda_T P_{10} + \lambda_R P_{12} - K_{13} P_{14} = 0$
15	S_{15}	$\lambda_C P_7 + \lambda_T P_{11} + \lambda_R P_{13} + \lambda_D P_{14} = 0$

The shutdown equation, represented by equation 15, was deemed redundant and therefore excluded from the set of transition state equations. To ensured that the sum of probabilities across all the states in the model always equals one, a conservative equation was formulated in equation 16

$$\sum_{i=0}^{14} P_i = 1 \tag{16}$$

Equation 16, could be rewritten as

$$P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 + P_9 + P_{10} + P_{11} + P_{12} + P_{13} + P_{14} = 1 \tag{17}$$

These sets of equations were solved in matrix form, as depicted in equation 18.

$$[C].\,[P] = [U] \tag{18}$$

For $[C]$ is the Markov transition matrix. These sets of equations 1-14 are transformed into matrix form as shown in equation 19.

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$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ \lambda_D & -k_0 & 0 & \mu_R & 0 & \mu_T & 0 & 0 & 0 & \mu_C & 0 & 0 & 0 & 0 & 0 \\ \lambda_R & 0 & -k_1 & \mu_D & 0 & 0 & \mu_T & 0 & 0 & 0 & \mu_C & 0 & 0 & 0 & 0 \\ 0 & \lambda_R & \lambda_D & -k_1 & 0 & 0 & 0 & \mu_T & 0 & 0 & 0 & \mu_C & 0 & 0 & 0 \\ \lambda_T & 0 & 0 & 0 & -k_2 & \mu_D & \mu_R & 0 & 0 & 0 & 0 & 0 & \mu_C & 0 & 0 \\ 0 & \lambda_T & 0 & 0 & \lambda_D & -k_5 & 0 & \mu_R & 0 & 0 & 0 & 0 & 0 & \mu_C & 0 \\ 0 & 0 & \lambda_T & 0 & \lambda_R & 0 & -k_6 & \mu_D & 0 & 0 & 0 & 0 & 0 & 0 & \mu_C \\ 0 & 0 & 0 & \lambda_T & 0 & \lambda_R & \lambda_D & -k_5 & 0 & \mu_R & 0 & 0 & 0 & \mu_C & 0 \\ \lambda_C & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_3 & \mu_D & \mu_R & 0 & \mu_T & 0 & 0 \\ 0 & \lambda_C & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_D & -k_7 & 0 & \mu_R & 0 & \mu_T & 0 \\ 0 & 0 & \lambda_C & 0 & 0 & 0 & 0 & 0 & \lambda_R & 0 & -k_8 & \mu_D & 0 & 0 & \mu_T \\ 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & 0 & 0 & \lambda_R & \lambda_D & -k_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & \lambda_T & 0 & 0 & 0 & -k_9 & \mu_D & \mu_R \\ 0 & 0 & 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & \lambda_T & 0 & 0 & \lambda_D & -k_9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & \lambda_T & 0 & \lambda_R & 0 & -k_{13} \end{bmatrix} \bullet \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \\ P_7 \\ P_8 \\ P_9 \\ P_{10} \\ P_{11} \\ P_{12} \\ P_{13} \\ P_{14} \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (19)$$

To determine the probabilities, the equations are re-arranged to obtain a simplified form

$$[P] = [C]^{-1} \cdot [U] \qquad (20)$$

The Markov transition matrix [C], obtained in equation 19, exhibits diagonal dominance. Typically, the system shutdown equation arose as a linear combination of state probabilities. In this case, the system shutdown equation and the row vector matrix [L] derived from shutdown transition state equation was expressed in equation 15 and equation 21

$$\lambda_C P_7 + \lambda_T P_{11} + \lambda_R P_{13} + \lambda_D P_{14} = 0 \qquad (15)$$

$$[L] = [\,0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ \lambda_C\ \ 0\ \ 0\ \ 0\ \ \lambda_T\ \ 0\ \ \lambda_R\ \ \lambda_D\,] \qquad (21)$$

The total system failure rate for the signal processing circuit is denoted by λ_{sys}, which can be calculated

as $\lambda_{sys}=[L].[C]^{-1}.[U]$ [29]

The matrix required to compute the circuit's total failure rate is illustrated in equation (24).

$$\begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \\ P_7 \\ P_8 \\ P_9 \\ P_{10} \\ P_{11} \\ P_{12} \\ P_{13} \\ P_{14} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ \lambda_D & -k_0 & 0 & \mu_R & 0 & \mu_T & 0 & 0 & 0 & \mu_C & 0 & 0 & 0 & 0 & 0 \\ \lambda_R & 0 & -k_1 & \mu_D & 0 & 0 & \mu_T & 0 & 0 & 0 & \mu_C & 0 & 0 & 0 & 0 \\ 0 & \lambda_R & \lambda_D & -k_1 & 0 & 0 & 0 & \mu_T & 0 & 0 & 0 & \mu_C & 0 & 0 & 0 \\ \lambda_T & 0 & 0 & 0 & -k_2 & \mu_D & \mu_R & 0 & 0 & 0 & 0 & 0 & \mu_C & 0 & 0 \\ 0 & \lambda_T & 0 & 0 & \lambda_D & -k_5 & 0 & \mu_R & 0 & 0 & 0 & 0 & 0 & \mu_C & 0 \\ 0 & 0 & \lambda_T & 0 & \lambda_R & 0 & -k_6 & \mu_D & 0 & 0 & 0 & 0 & 0 & 0 & \mu_C \\ 0 & 0 & 0 & \lambda_T & 0 & \lambda_R & \lambda_D & -k_5 & 0 & \mu_R & 0 & 0 & 0 & \mu_C & 0 \\ \lambda_C & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_3 & \mu_D & \mu_R & 0 & \mu_T & 0 & 0 \\ 0 & \lambda_C & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_D & -k_7 & 0 & \mu_R & 0 & \mu_T & 0 \\ 0 & 0 & \lambda_C & 0 & 0 & 0 & 0 & 0 & \lambda_R & 0 & -k_8 & \mu_D & 0 & 0 & \mu_T \\ 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & 0 & 0 & \lambda_R & \lambda_D & -k_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & \lambda_T & 0 & 0 & 0 & -k_9 & \mu_D & \mu_R \\ 0 & 0 & 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & \lambda_T & 0 & 0 & \lambda_D & -k_9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & \lambda_T & 0 & \lambda_R & 0 & -k_{13} \end{bmatrix}^{-1} \bullet \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (23)$$

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$$\lambda_{sys}=\begin{bmatrix}0 & 0 & 0 & 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & \lambda_T & 0 & \lambda_R & \lambda_D\end{bmatrix}\bullet\begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1\\
\lambda_D & -k_0 & 0 & \mu_R & 0 & \mu_T & 0 & 0 & 0 & \mu_C & 0 & 0 & 0 & 0 & 0\\
\lambda_R & 0 & -k_1 & \mu_D & 0 & 0 & \mu_T & 0 & 0 & 0 & \mu_C & 0 & 0 & 0 & 0\\
0 & \lambda_R & \lambda_D & -k_1 & 0 & 0 & 0 & \mu_T & 0 & 0 & 0 & \mu_C & 0 & 0 & 0\\
\lambda_T & 0 & 0 & 0 & -k_2 & \mu_D & \mu_R & 0 & 0 & 0 & 0 & 0 & \mu_C & 0 & 0\\
0 & \lambda_T & 0 & 0 & \lambda_D & -k_5 & 0 & \mu_R & 0 & 0 & 0 & 0 & 0 & \mu_C & 0\\
0 & 0 & \lambda_T & 0 & \lambda_R & 0 & -k_6 & \mu_D & 0 & 0 & 0 & 0 & 0 & 0 & \mu_C\\
0 & 0 & 0 & \lambda_T & 0 & \lambda_R & \lambda_D & -k_5 & 0 & \mu_R & 0 & 0 & 0 & \mu_C & 0\\
\lambda_C & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_3 & \mu_D & \mu_R & 0 & \mu_T & 0 & 0\\
0 & \lambda_C & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_D & -k_7 & 0 & \mu_R & 0 & \mu_T & 0\\
0 & 0 & \lambda_C & 0 & 0 & 0 & 0 & 0 & \lambda_R & 0 & -k_8 & \mu_D & 0 & 0 & \mu_T\\
0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & 0 & 0 & \lambda_R & \lambda_D & -k_{11} & 0 & 0 & 0\\
0 & 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & \lambda_T & 0 & 0 & 0 & -k_9 & \mu_D & \mu_R\\
0 & 0 & 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & \lambda_T & 0 & 0 & \lambda_D & -k_9 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & \lambda_C & 0 & 0 & 0 & \lambda_T & 0 & \lambda_R & 0 & -k_{13}
\end{bmatrix}^{-1}\bullet\begin{bmatrix}1\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\end{bmatrix} \quad (24)$$

RESULT OBTAINED AND DISCUSSIONS

The various failure rates of the circuit's constituent components were gotten from Military Reliability Data Handbook. These data were randomly chosen and grouped into four, based on the various values of the circuit's components inorder to determine the reliability metrics of each group in terms of the total failure rate of the circuit and mean time between failure of such circuit. They were as presented in Table 3 to Table 6. The maintenance strategy assumed for this circuit had been discussed earlier in Section 2.

Table 3: Total Failure Rate of Signal Processing Circuit (Type 1 Components).

Component	Failure rate, λ (failures/10^6)	Inspection time, *t* (hrs)	Repair rate, μ = 2/*t* (per hr)	Total failure rate, λ_{sys}. of the circuit
Capacitor, C	0.0037	500	0.004	8.3901×10^{-4} /hr.
Transistor, T	0.031	500	0.004	
Resistor, R	0.0017	1000	0.002	
Diode, D	0.0038	1000	0.002	

Table 4: Total Failure Rate to Signal Processing Circuit (Type 2 Components)

Component	Failure rate, λ (failures/10^6)	Inspection time, *t* (hrs)	Repair rate, μ = 2/*t* (per hr)	Total failure rate, λ_{sys}. of the circuit
Capacitor, C	0.0051	500	0.004	3.3675×10^{-4} /hr.
Transistor, T	0.019	500	0.002	
Resisor, R	0.005	1000	0.002	
Diode, D	0.001	1000	0.004	

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Table 5: Total failure rate of the signal processing circuit (Type 3 components)

Component	Failure rate, λ (failures/10^6)	Inspection time, t (hrs)	Repair rate, μ $2/t$= (per hr)	Total failure rate, λ_{sys}. of the circuit
Capacitor, C	0.00076	500	0.004	3.5691×10^{-4} /hr.
Transistor, T	0.11	500	0.004	
Diode, D	0.0034	1000	0.002	
Resistor, R	0.0024	1000	0.002	

Table 6: Total failure rate of the signal processing circuit (Type 4 components).

Component	Failure rate, λ (failures/10^6)	Inspection time, t (hrs)	Repair rate, μ $2/t$= (per hr)	Total failure rate, λ_{sys}. of the circuit
Capacitor, C	0.0079	500	0.004	2.8538×10^{-3} /hr.
Transistor, T	0.49	500	0.004	
Diode, D	0.025	1000	0.002	
Resistor, R	0.0039	1000	0.002	

The complexity of the calculations required for Markov analysis makes it necessary for software to be used for effective modeling of such problems. Traditional manual methods have been found wanting in solving Markov analysis problems because of the complexity of the Markov chain structure and the calculations involved in such analysis. As such, several software solutions have been developed to help solve matrix calculations for the precise determination of the total failure rate of complex systems. Among the several software options available for solving Markov analysis problems, MATLAB stands out as a very effective tool for solving such problems because of its advanced computational capabilities, which make it very effective in handling the complex calculations of Markov analysis problems.

A. Data Assimilation

The failure rate is the number of failures per unit time. The failure rate for the circuit's components such as the resistor, capacitor, inductor, and transistor is based on the Military Handbook (usually cited as **MIL-HDBK-217F**, or "Reliability Prediction of Electronic Equipment"). The simulation data were divided into four classes (type 1, type 2, type 3, and type 4) according to the failure rate and the repair rate per hour for the circuit's components.

B. Reliability and Mean Time Between Failures (MTBF) of the Signal Processing Circuit

The reliability of the equipment also plays an important role, which is represented by the reliability parameter. However, the effectiveness of the reliability parameter is highly dependent on the time period, which makes it less applicable in different scenarios. To make the reliability more applicable, the Mean Time Between Failures (MTBF) concept is often used. MTBF provides a useful reliability metric, which shows the average time between successive failures. This metric is highly useful in the case of maintained systems, where the failed system is repaired, making it ready for operation. By using the MTBF concept, the reliability of the system is better understood, which provides the users with better insights into the system. This makes the system more useful for ensuring the reliability of the equipment, which ultimately provides the users with better satisfaction.

The failure rate (λ) is one of the primary parameters of reliability, especially in the case of evaluating the reliability of different components. It provides the users with the advantage of estimating the reliability of the entire system by using the characteristics of the different components. It is defined as follows:

$$\lambda = \frac{1}{MTBF} \tag{25}$$

Using the data presented in Tables 3 through 6, the Mean Time Between Failures (MTBF) for the entire circuit can be determined. MTBF is an essential parameter that defines the average time period between two consecutive failures. Therefore, it provides a holistic assessment of the reliability of the circuit over time. This calculation not only emphasizes the reliability of the Tables 3–6 configuration but also provides a predictive measure regarding the longevity of the circuit.

MTBF is essential for the maintenance of the circuit as it can be used to schedule the replacement of the components in the signal processing circuit. Therefore, the overall integrity of the circuit can be maintained using the insights obtained from the failure rate analysis presented in Tables 3 through 6.

Moreover, the assessment of the overall failure rate of the signal processing circuit presented in Table 4 indicates that the specifications presented in Table 4 provide a highly reliable circuit. Therefore, the MTBF for the entire circuit can be determined.

$$MTBF = \frac{1}{\lambda_{sys}} \tag{26}$$

where λ_{sys} = Total failure rate of the circuit.

The total failure rate, λ_{sys} of 3.3675 x 10^{-4}/hr (Table 4) is taken into consideration. Then,

$$MTBF = \frac{1}{3.3675\times10^{-4} \big/ hr} = 2970 hrs \tag{27}$$

C. Exponential Distribution Characteristics of the Circuit

The circuit was assumed to exhibit an exponential distribution behavior as dictated by the constant failure rate model during continuous operation. Mathematically, the reliability can be expressed as follows:

$R(t)= e^{-\lambda t}$, where λ = failure rate (/hr), t = operating period (hr). (28)

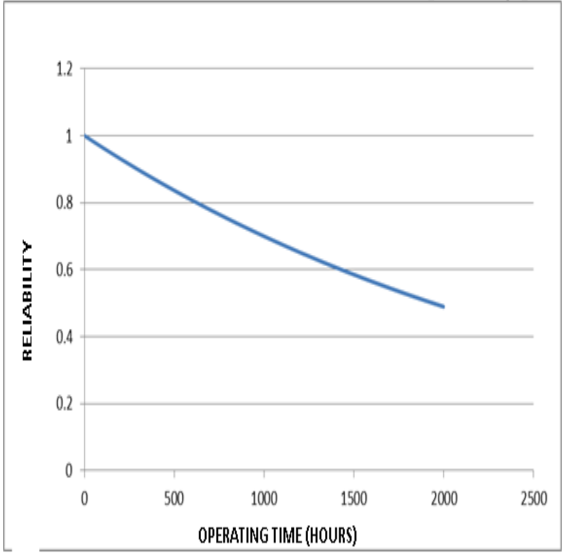

Figure 5. Reliability Plot for Signal Processing Circuit with a total failure rate of 8.3901x10^{-4}/hr

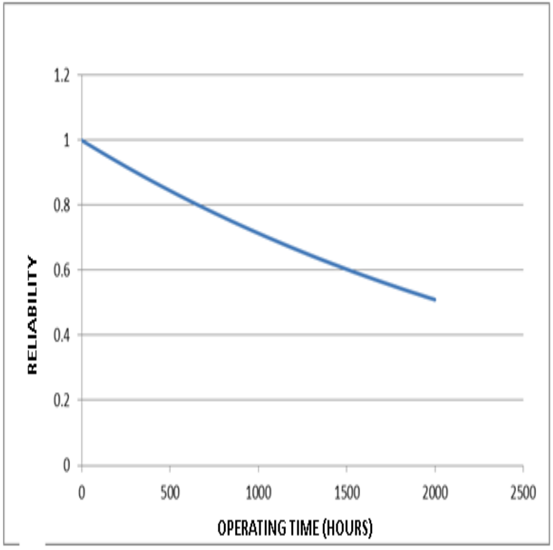

Figure 6. Reliability Plot for Signal Processing Circuit with a total failure rate of 3.3676x10^{-4}/hr

An analysis of the reliability plots of the circuit in Figure 2, over an extensive period of operation t, and using the constant failure rate model, reveals several vital insights into the performance of the circuit. The distribution of the failure times, defined by a single parameter λ, was previously calculated in Tables 3, 4, 5, and 6. This parameter is vital in defining the exponential behavior of the circuit's reliability over a period of operation. The reliability plots of the circuit, as shown in Figures 5, 6, 7, and 8, clearly demonstrate an exponential decrease in reliability over a period of operation. These plots provide a clear visualization of the decrease in reliability during operation, thus ensuring a complete analysis of the circuit's performance over a long period of operation.

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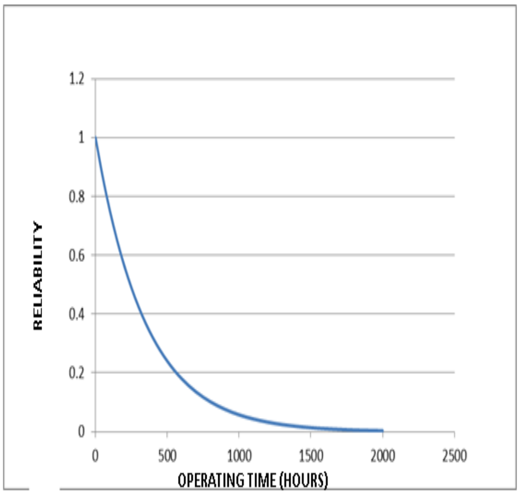

Figure 7. Reliability Plots for Signal Processing Circuit with a total failure rate of 3.5691x10^{-4}/hr

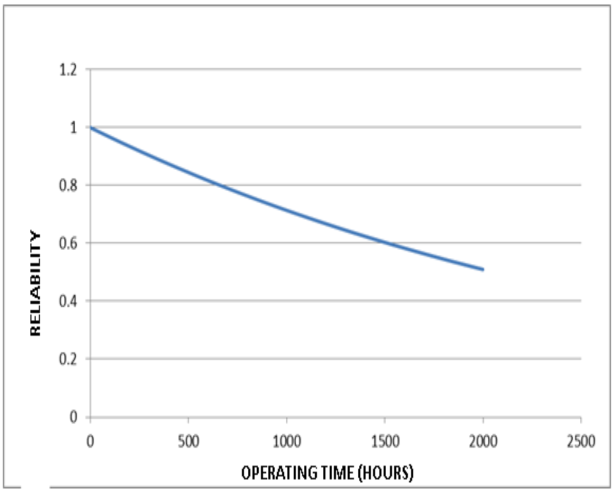

Figure 8. Reliability Plots for Signal Processing Circuit with a total failure rate of 2.8536x10^{-3}/hr

The results provided by the reliability plot give an overview of the values of the circuit configurations' reliability over a set period of time. On the basis of the results provided, it is clear that the circuit using type 2 components is capable of attaining a higher value of reliability, i.e., 0.9833, after the operation of the circuit for 50 hours, as shown in Figure 6. This is in comparison to the results provided for the circuits using type 1 components, which attain a reliability value of 0.958, as shown in Figure 5, type 3 components, which attain a reliability value of 0.9823, as shown in Figure 7, and type 4 components, which attain a significantly lower reliability value, i.e., 0.8671, after the operation of the circuit for 50 hours, as shown in Figure 8. The results provided by the comparative study show the significance of using the appropriate type of components in the circuit in order to ensure better reliability and efficiency, which can result in better performance and lower failure rates over a longer period.

Likewise, in a 1000-hour operating period, the circuit involving type 2 components shows a significantly higher reliability value of 0.7141. This shows a remarkably better reliability value in comparison to other types of circuit configurations involving different types of components. For example, in a circuit involving type 1 components, a reliability value of 0.4321 is obtained, whereas a circuit involving type 3 components shows a reliability value of 0.6998. Furthermore, a circuit involving type 4 components shows a significantly lower reliability value of 0.0576. These results are depicted in figures and show that the signal processing circuit involving a total failure rate of 3.3675x10^-4 per hour is significantly more reliable in comparison to other types of circuit configurations. This analysis shows that the selection of specific types of components is crucial in order to enhance the reliability of electronic systems. The better reliability of type 2 components shows that they are more suitable for use in electronic systems that require high reliability over a long period of operation and are therefore more suitable in designing signal processing circuits.

Thus, in conclusion, Table 7 shows the results of the calculation of the total failure rate, mean time between failures, and reliability coefficient of each of the different types of circuit configurations involving Type 1 components, Type 2 components, Type 3 components, and Type 4 components.

Table 7 : Evaluation of Failure Rate, MTBF, and Reliability Coefficient for Component Types

Configuration	Type 1 components	Type 2 components	Type 3 components	Type 4 components
Failure rate, λ (× 10^{-4}/hr)	8.3901	3.3675	3.5691	28.538
MTBF (hrs)	1191.9	2969.6	2801.8	350.4
Reliability coefficient	0.4321	0..7141	0.6998	0.0576

Table 7 presents a comparative analysis of reliability metrics for four different component types, evaluated based on three key parameters. Type 2 and Type 3 have the lowest failure rates at 3.3675 and 3.5691, respectively.

Conversely, Type 4 has the highest failure rate at 28.538, implying poor reliability. Further analysis of Table 7 shows that Type 2 has the highest Mean Time Between Failures (MTBF) at 2969.6 hours. This is in line with the lowest failure rate. Type 4 has the lowest MTBF at 350.4 hours, implying that the type has the highest failure rate. Concerning the reliability coefficient, Type 2 has the highest coefficient at 0.7141. Conversely, Type 4 has the lowest coefficient at 0.0576. Based on the results obtained in this study, Type 2 components have the highest reliability compared to other types. This is due to the lowest failure rate, the highest MTBF, and the highest reliability coefficient. Conversely, Type 4 components have the lowest reliability compared to other types.

CONCLUSION

For the investigation, a continuous-time Markov model was used to analyze a four-component signal processing circuit consisting of a capacitor, NPN transistor, resistor, and diode. A transition diagram consisting of 16 states was developed, from which matrix equations were solved to obtain the total system failure rate ($\lambda = 3.3675 \times 10^{-4}$ hr^{-1}) and a mean time between failures (MTBF ≈ 2,970 h) for the configuration of "Type 2" components. This configuration also showed the lowest failure rate of 3.3675 per 10^6 hours and the highest reliability of the four component groups investigated. Markov modeling has been identified as a powerful tool for dynamic reliability analysis of electronic systems, overcoming static limitations of fault trees and reliability block diagrams. More recently, similar Markov modeling approaches have been adopted for reliability analysis of power systems in smart grid systems, wireless sensor networks, and avionics systems, which have been successfully demonstrated in several studies. This investigation adds to this literature by focusing on a compact signal processing circuit, presenting detailed component failure and repair rate data from the Military Reliability Handbook.

For this study, the signal processing circuit with four constituent components was chosen for modeling. Each component has two different states: one where the component is operational or functioning, and one where the component is not functioning or has failed. For the component that is not functioning or has failed, there is the inclusion of the rate at which the component is being repaired (μ). By making the assumptions as required, the circuit is modeled from an initial state where all four components are functioning optimally to one where the components are in a state of failure. The modeling resulted in the formation of the transition state diagram with 16 states. Consequently, homogeneous transition state equations, a shutdown equation, and state probability equations were derived. Furthermore, the transition state matrix, row vector matrix, and unit matrix were developed as integral components of the modeling framework.

Based on the findings, it can be concluded that the reliability of an electronic circuit is dependent on the failure rate and repair rate of its constituent components. This type of reliability assessment technique takes into account the probabilistic behaviour of component failures and their subsequent repairs. By quantifying the failure and repair characteristics of the components, a comprehensive evaluation of the circuit's reliability can be achieved. Hence useful to system design and reliability Engineers.

RECOMMENDATIONS FOR FUTURE RESEARCH

Markov modelling technique can generate all the possible states of a system; the number of states can be extremely large for a relatively small number of Markov components (constituent components of the system). Thus, researchers using this Markov modelling techniques must become familiar with reduction techniques that can be applied to reduce the number of states significantly while maintaining the accuracy of the model. Moreover, a transient (time-dependent) analysis of an open-loop model (without repairs) is an area that researchers can explore. For instance, when determining the minimum acceptable system configuration for operation and the length of time allowed for such operation, researchers may wish to know not just the total system failure rate but also the worst case instantaneous system failure rate as a function of time for a given configuration, incorporate phase-type and non-exponential distributions to capture realistic, time-varying failure rates; integrate uncertainty-quantification (e.g., Bayesian) methods for robust parameter estimation; and implement advanced computational tools (e.g., MATLAB, machine-learning-based solvers) to automate and scale the analysis.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis

I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting

Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article, and they are obtained from Reliability Military Handbook.

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