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Mean Time To System Failure And Availability Analysis Of A Repairable 2:4:: Good System

Hari Krishana[1], Dr. Arun Kumar[2]

[1]Research Scholar, Department of Mathematics, Shri Khushal Das University, Hanumangarh
[2]Research Supervisor, Department of Mathematics, Shri Khushal Das University, Hanumangarh

ABSTRACT

This study analyzes the mean time to system failure (MTSF) and availability of a repairable 2-out-of-4 (2:4) good redundant system using the Regenerative Point Graphical Technique (RPGT) and Markov processes. The system, relevant to Rajasthan's industrial sector, consists of four identical units where any two must function for system success and the remaining two act as cold standbys. The model incorporates practical assumptions including a single always-available repairman, prioritized repair order, and constant failure and repair rates. The results provide actionable guidance for maintenance scheduling, resource allocation, and operational policy, supporting managers in optimizing uptime and efficiency for critical infrastructure systems.

Keywords: 2-out-of-4 good system, Redundancy, Mean time to system failure, System availability, RPGT, Markov process, Repairable systems

1. INTRODUCTION

Ensuring high reliability in critical industrial systems is vital, especially in regions like Rajasthan, India, where environmental challenges, resource constraints, and the need for uninterrupted operations are significant. Redundant system designs, such as the 2:4 good system, are widely adopted to mitigate risks of downtime by enabling continued operation as long as any two of four units function. This study focuses on the mathematical modeling and behavior analysis of a repairable 2:4 good system, tailored for Rajasthan's industries, where a single repair technician is responsible for restoring failed units based on priority. By using the Regenerative Point Graphical Technique (RPGT) and Markov modeling, the research quantifies key reliability metrics—including mean time to system failure (MTSF) and availability—under varying operational scenarios. These insights support industrial managers in making informed decisions related to maintenance policies and system design, maximizing both reliability and operational efficiency. Arya and Verma (2025) highlighted the importance of environmental factors in the reliability and availability prediction of embedded systems, utilizing simulation-based approaches to account for real-world operational complexities. The role of preventive maintenance and system degradation has been examined by Goyal, Goel, and Goel (2015), who analyzed a two-unit system and demonstrated that incorporating preventive maintenance strategies significantly improves system behavior and lifecycle performance, even when one unit is subject to degradation. Several studies have focused on sensitivity analysis and behavioral modeling of multi-unit and standby systems. Kumar, Garg, and Goel (2019) conducted a sensitivity analysis of a cold standby system with prioritized preventive maintenance, providing insights into how varying maintenance protocols can influence overall system reliability. Kumar, Garg, Goel, and Ozer (2018) extended this work to 3:4 good systems, offering a quantitative framework for understanding the effects of repair and failure rates on system performance under different operational scenarios. Industrial applications of mathematical modeling have been further explored by Kumar, Garg, and Goel (2019) in the context of a washing unit in a paper mill, revealing the practical value of reliability and behavioral analysis in optimizing plant operations. Kumar (2022) applied the Regenerative Point Graphical Technique (RPGT) to analyze the performance of a rice processing plant, demonstrating the adaptability of RPGT across agro-industrial systems. Optimization techniques are also prominent in reliability research. Kumari et al. (2021) explored particle swarm optimization for constrained problems, illustrating its effectiveness in solving complex reliability and resource allocation issues. Saini, Kumar, and Sinwar (2022) contributed to the field by providing parameter estimation and reliability analysis for a sugar manufacturing plant, underscoring the importance of data-driven approaches for maintainability and operational decision-making.

2. SYSTEM DESCRIPTION

The repairable 2:4 good system comprises four identical units (A, B, C, D), with two units active and two in cold standby at any time. The system remains fully operational as long as any two units are functioning; standby units are instantly switched in upon failure of an active unit. Maintenance is performed by a single always-available repairman, who restores failed units to as-good-as-new condition according to a strict priority order. The model assumes independent, constant failure and repair rates for all units and neglects preventive maintenance, focusing instead on corrective actions. State transitions are governed by failures and repairs, with the system state diagram mapping all possible configurations and transitions. This structure enables detailed reliability and availability analysis, providing a practical foundation for optimizing maintenance and system performance in demanding industrial environments.

3. NOTATIONS & ASSUMPTIONS:

- The system comprises four identical units labeled A, B, C, and D.
- Failure and Repair Parameters:
- β_i Constant repair rates for type i, i=2, 3, 4, 5
- α_i constant failure rates for types i, i=2, 3, 4, 5

4. SYSTEM TRANSITION STATE DIAGRAM

The analysis of a repairable 2:4 good redundant system begins with constructing a comprehensive system transition state diagram. This diagram serves as the foundational framework for understanding the dynamic behavior of the system under various operational and failure conditions. The systematic arrangement of states and transitions allows for the application of Markov and RPGT techniques to analyze system reliability, downtime, and maintenance needs Accounting assumptions & notations in study Transition State Diagram of system is given in Figure 1.

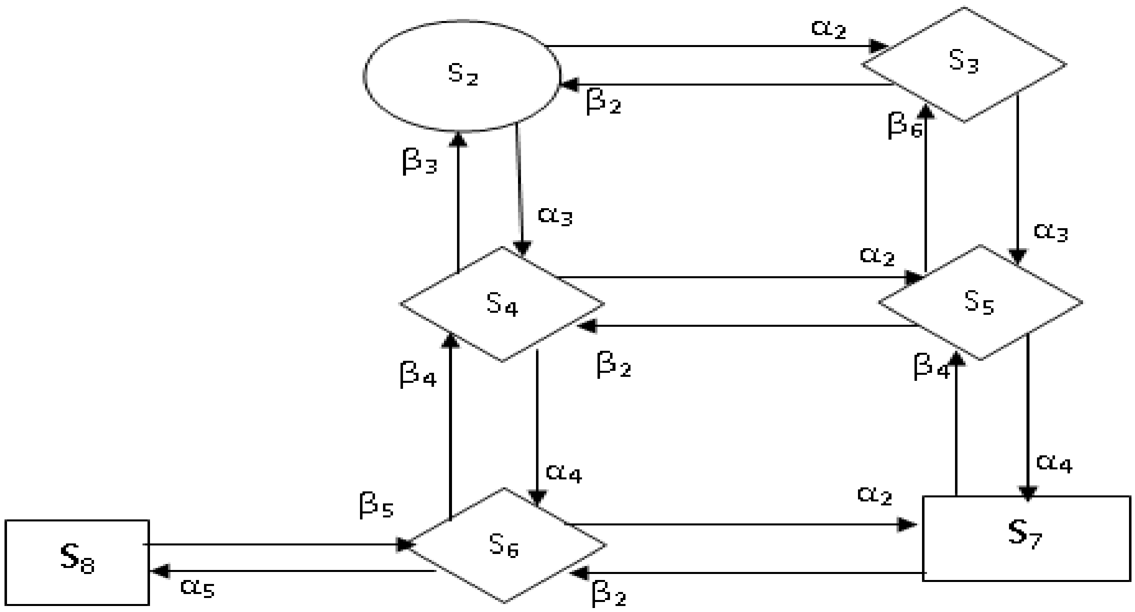

Figure 1: System Transition State Diagram

5. EVALUATION OF PARAMETERS:

$V_{2,2}$ =1 (Verified)

$V_{2,3}$ = (2,3)/[1-(3,5,3)/{1-(5,4,5)}{1-(5,7,6,4,5)}]+(2,4,5,3)/[{1-(4,6,7,5,4)}/{1-(6,8,6)}]+(2,4,6,7,5,3)/{1-(6,8,6)}

$V_{2,4}$ = …..Continuous

6. MODELING AND RESULTS

MTSF (T_0) : The un-failed states to which system transits, before visiting any failed state are : $2 \leq j \leq 6$,taking ξ' =2,we have.

$$\text{MTSF}(T_0) = \left[\sum_{i,sr}\left\{\frac{\left\{pr\left(\xi \xrightarrow{sr(sff)} i\right)\right\}\mu i}{\prod_{m_1 \neq \xi}\{1 - V_{\overline{m_1 m_1}}\}}\right\}\right] \div \left[1 - \sum_{sr}\left\{\frac{\left\{pr\left(\xi \xrightarrow{sr(sff)} \xi\right)\right\}}{\prod_{m_2 \neq \xi}\{1 - V_{\overline{m_2 m_2}}\}}\right\}\right]$$

Availability of System (A_0) : The states are where system is available are $2 \leq j \leq 6$ taking base state ξ' = 6 'total fraction of time for which system is available

$$A_0 = \left[\sum_{j,sr}\left\{\frac{\{pr(\xi^{sr\rightarrow}j)\}fj,\mu j}{\Pi_{m_{1\neq\xi}}\{1-V_{\overline{m_1 m_1}}\}}\right\}\right] \div \left[\sum_{i,s_r}\left\{\frac{\{pr(\xi^{sr\rightarrow}i)\}\mu_i^1}{\Pi_{m_{2\neq\xi}}\{1-V_{\overline{m_2 m_2}}\}}\right\}\right]$$

7. PARTICULAR CASES

Specific Cases:-α_i $(2 \leq i \leq 5) = \alpha$; β_i $(2 \leq i \leq 5) = \beta$

Table 1: Mean Time to System Failure (T_0)

T_0	β = 0.85	β = 0.90	β = 0.95	β = 1.00
α = 0.35	4.70	4.68	4.66	4.64
α = 0.40	3.56	3.54	3.52	3.50
α = 0.45	2.79	2.77	2.75	2.73
α = 0.50	1.92	1.90	1.88	1.86

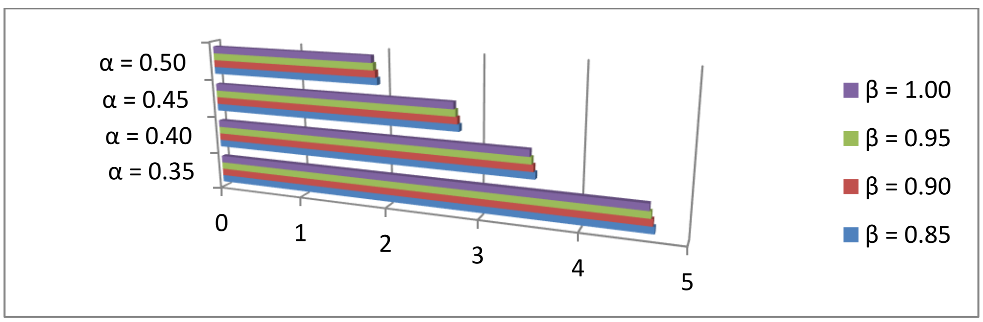

Figure 2: Mean Time to System Failure (T_0)

Table 1 presents the Mean Time to System Failure (T_0) for the repairable 2:4 good system under various combinations of constant failure rates (α) and repair rates (β). The table demonstrates that as the repair rate (β) increases, the system's mean time to failure also increases, indicating enhanced reliability due to quicker restoration of failed units. Conversely, as the failure rate (α) increases, the mean time to system failure decreases, reflecting the detrimental impact of more frequent unit breakdowns. This relationship, as depicted in Figure 2, highlights the crucial role of efficient maintenance and low failure incidence in ensuring the longevity and reliability of redundant systems, particularly in demanding operational environments such as Rajasthan, India.

Table 2: Availability of the System (A_0)

A_0	β = 0.85	β = 0.90	β = 0.95	β = 1.00
α = 0.35	2.89	2.93	2.96	2.99

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α = 0.40	2.64	2.70	2.74	2.77
α = 0.45	2.39	2.46	2.50	2.55
α = 0.50	2.14	2.18	2.23	2.29

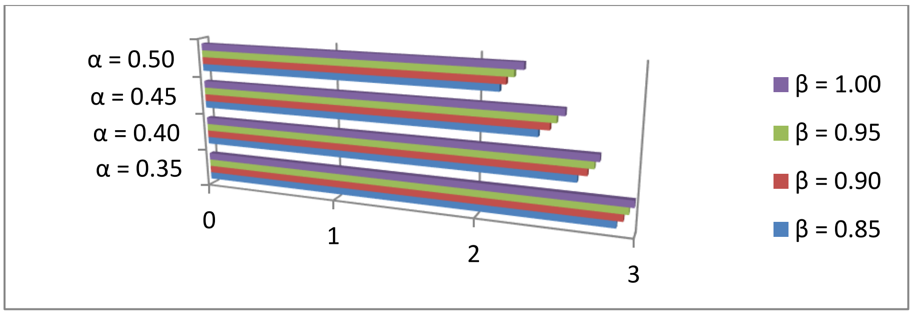

Figure 3: Availability of the System (A_0)

Table 2 provides the calculated values for the availability of the 2:4 good system (A_0) under different combinations of constant failure rates (α) and repair rates (β). The data clearly shows that system availability improves as the repair rate increases, reflecting the system's ability to return to operational status more quickly after failures. Conversely, higher failure rates result in decreased availability, as the system spends more time in degraded or non-operational states. The results confirm that optimizing the repair process and controlling unit reliability are essential strategies for achieving high system availability in practice.

8. CONCLUSION

Managing a system composed of multiple sub-units, both large and small, is inherently complex. Stakeholders are continually seeking ways to enhance system performance, often considering options such as increasing the repair rates of sub-units—despite the potential for higher associated costs. Decisions to invest in more efficient repair strategies must be weighed against anticipated gains in profitability, operational reliability, and market competitiveness. By carefully monitoring and optimizing key system parameters, stakeholders can make informed choices about resource allocation and maintenance policies. The analysis using the Regenerative Point Graphical Technique (RPGT) demonstrates that while failure rates are typically beyond direct managerial control, improving repair rates offers a practical and impactful approach to optimizing system performance. Ultimately, the ability to achieve optimal system outcomes depends on strategic management of repair capabilities, balanced against financial resources and prevailing market conditions.

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