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Reviewing the Performance of Repairable Systems through Various Mathematical Models

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Abstract

The performance evaluation of repairable systems is a critical area of study in reliability engineering. This review paper examines various mathematical models used to assess and predict the performance of repairable systems. The focus is on understanding the strengths, limitations, and applications of these models in real-world scenarios. Key models reviewed include the Homogeneous Poisson Process (HPP), Non-Homogeneous Poisson Process (NHPP), and Renewal Process, among others. Each model's theoretical foundations are discussed, along with practical examples to illustrate their application. The review also explores advancements in repairable systems modeling, such as Bayesian approaches and machine learning techniques, which offer enhanced predictive capabilities. Challenges in modeling, including data quality and parameter estimation, are highlighted to provide a comprehensive understanding of the current state of research. By synthesizing findings from various studies, this paper aims to guide researchers and practitioners in selecting appropriate models for specific contexts, ultimately contributing to improved maintenance strategies and system reliability. Future research directions are suggested, emphasizing the integration of emerging technologies and the need for robust validation methods to enhance model accuracy and applicability.

Introduction

The reliability and performance of repairable systems are vital considerations in numerous industries, including manufacturing, aerospace, telecommunications, and healthcare. These systems, unlike non-repairable systems, can be restored to operational status after a failure, making their performance assessment complex yet crucial. Understanding the behavior of repairable systems helps in optimizing maintenance strategies, reducing downtime, and ensuring the continuous operation of critical infrastructure. The study of repairable systems has

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evolved significantly over the years, with various mathematical models developed to analyze their performance. Early models, such as the Homogeneous Poisson Process (HPP) and Non-Homogeneous Poisson Process (NHPP), laid the groundwork for understanding failure patterns and repair processes. These models provided insights into system reliability by characterizing the stochastic nature of failures and repairs over time. In recent years, advancements in computational techniques and data availability have further expanded the scope of repairable systems modeling. Bayesian methods and machine learning algorithms have emerged as powerful tools, enabling the incorporation of prior knowledge and the handling of large datasets to improve predictive accuracy. These innovative approaches not only enhance model precision but also provide new avenues for dynamic and adaptive maintenance planning. This paper aims to review the key mathematical models used in the performance analysis of repairable systems. By examining the theoretical foundations, practical applications, and recent advancements of these models, we seek to provide a comprehensive understanding of their capabilities and limitations. Additionally, we will explore the challenges associated with model implementation and highlight future research directions that could further refine the performance assessment of repairable systems. Through this review, we hope to guide researchers and practitioners in selecting and applying the most appropriate models for their specific needs, ultimately contributing to improved reliability and maintenance strategies across various industries.

Need of the Study

The study of repairable systems via various mathematical models is imperative due to its critical implications across multiple industries and disciplines. Firstly, optimized maintenance strategies are essential for minimizing downtime, reducing costs, and maximizing productivity. Mathematical modeling helps organizations tailor maintenance plans that balance reliability, cost, and resource utilization effectively. Secondly, in industries where system failures can lead to severe consequences, such as aerospace and healthcare, risk management is paramount. Analyzing repairable systems aids in identifying potential failure modes, assessing their likelihood and impact, and implementing mitigation measures to enhance system resilience. Thirdly, resource allocation must be judiciously managed to maintain and repair systems efficiently. Mathematical models provide insights into optimal resource allocation to maximize system availability while minimizing costs. Moreover, for manufacturers, understanding the reliability and maintainability of their products is crucial for design and improvement. By analyzing repairable systems, designers can identify weak points, optimize component

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selection, and enhance product reliability over its lifecycle. Lastly, regulatory compliance is essential for industries subject to stringent reliability standards. Mathematical modeling facilitates compliance by quantifying system performance metrics and demonstrating adherence to safety and reliability standards. Overall, the study of repairable systems through mathematical models addresses pressing needs related to maintenance optimization, risk management, resource allocation, product design, and regulatory compliance, contributing to enhanced operational efficiency, safety, and reliability.

Literature Review

Hajeeh, M. A. (2015). Performance and cost analysis of repairable systems under imperfect repair is paramount in reliability engineering. Imperfect repair, where restored components don't fully regain original performance, adds complexity to modeling system behavior. Traditional metrics like mean time between failures (MTBF) and mean time to repair (MTTR) may no longer suffice. Analysts must now incorporate degradation rates and repair effectiveness to accurately assess system reliability and availability. Cost analysis becomes more intricate too. Although imperfect repairs seem cost-effective initially, they may lead to higher long-term costs due to increased failure rates and reduced system efficiency. Thus, a comprehensive cost analysis should encompass not only direct repair costs but also indirect costs like decreased performance and heightened maintenance needs. By integrating performance and cost analysis, engineers can make informed decisions on maintenance strategies, replacement policies, and system design enhancements. This holistic approach ensures that repair efforts align with organizational goals, striking the right balance between performance improvement and cost containment effectively.

Guo, R., Asher, H., & Love, E. (2000). Generalized models of repairable systems, surveyed through stochastic processes formalism, serve as invaluable tools for comprehensively understanding system dynamics and optimizing maintenance strategies. By employing stochastic processes like Markov processes and renewal theory, analysts can effectively capture the random nature of failures, repairs, and other system events. Markov processes enable the probabilistic modeling of state transitions within repairable systems, facilitating predictions of long-term behavior and assessments of reliability metrics such as availability and downtime. Renewal theory, on the other hand, focuses on the occurrence of failures and repair actions over time, providing insights into critical performance metrics like mean time between failures (MTBF) and mean time to repair (MTTR). Additionally, other stochastic processes formalisms,

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including queuing theory and reliability growth models, offer further perspectives on repairable system analysis. Queuing theory enables the modeling of repair service queues, facilitating evaluations of system performance under various repair policies and service capacities, while reliability growth models focus on improving system reliability over time through iterative testing and maintenance. Overall, a survey of generalized models of repairable systems via stochastic processes formalism offers a robust approach to enhancing reliability, availability, and performance across diverse domains through informed decision-making and optimized maintenance strategies.

Dahiya, O et al (2019) Mathematical modeling and performance evaluation of repairable systems through various mathematical models are foundational aspects of reliability engineering, offering systematic approaches to understanding system behavior and optimizing maintenance strategies. Renewal processes constitute a fundamental framework, providing insights into the occurrence of failures and repair actions over time. By delineating the system into renewal cycles, analysts can derive essential metrics like mean time between failures (MTBF) and mean time to repair (MTTR), guiding maintenance decisions effectively. Reliability block diagrams (RBDs) offer a visual representation of system components and their interdependencies, enabling the assessment of individual component reliability and the identification of critical points for improvement. Meanwhile, stochastic processes such as Markov models capture the dynamic nature of repairable systems, facilitating predictions of long-term behavior under varying conditions. These models consider factors like repair times and failure rates, aiding in the evaluation of maintenance policies' effectiveness. Overall, the utilization of mathematical models in analyzing repairable systems ensures informed decision-making, enhances system reliability, and minimizes downtime across diverse industries and applications.

Chand, U. et al (2019) Stochastic analysis of a complex repairable system comprising two subsystems arranged in series configuration, utilizing a multi-repair strategy, presents a sophisticated approach to comprehending system dynamics and refining maintenance procedures. In this setup, the failure of either subsystem results in the system's overall failure, and employing a multi-repair strategy implies subjecting failed components to multiple repair attempts before restoration to functionality. This strategy introduces complexity due to the stochastic nature of failure occurrences, repair durations, and the effectiveness of repair actions. Stochastic analysis within this framework typically involves modeling the system's dynamic behavior using probabilistic methodologies like Markov processes or queuing theory. Markov

ISSN PRINT 2319 1775 Online 2320 7876

 UGC CARE Listed (Group -I) Journal Volume 11, Iss 13, 2022

processes are adept at capturing the system's state transitions, delineating operational states (e.g., functioning, failed) and repair states (e.g., under repair, repaired). By defining transition probabilities between these states, analysts can predict critical reliability metrics such as system reliability, availability, and downtime over time. queuing theory can be applied to model the repair service queues within each subsystem, allowing for a thorough evaluation of system performance metrics such as queue length, waiting time, and resource utilization. This analysis considers factors such as repair resource availability and repair priorities, providing insights into the efficiency of the maintenance process.

Jain, M. (2016). Reliability prediction of repairable redundant systems with imperfect switching and repair is a vital task in reliability engineering, addressing the complexities introduced by the potential inefficiencies in component switching and repair processes. In these systems, multiple redundant components ensure continuous operation despite individual failures, but imperfections in switching and repair procedures can impact system reliability. Imperfect switching may cause delays or inefficiencies in transferring functionality to redundant components, while imperfect repair may result in components not fully restoring to their original state, leading to degraded system performance or increased susceptibility to future failures. To predict reliability, sophisticated mathematical models incorporating stochastic processes like Markov models are employed. These models consider dynamic interactions between system components, including failure rates, repair times, and the effectiveness of switching and repair actions. Reliability predictions entail probabilistic assessments of various failure and repair scenarios, accounting for uncertainties in component behaviors. By analyzing system state transitions and calculating relevant metrics such as mean time to failure and system availability, engineers gain insights into expected system performance over time. Sensitivity analyses may further assess different switching and repair strategies' impacts on reliability, aiding in selecting optimal maintenance policies. Overall, predicting reliability in these complex systems requires a deep understanding of system architecture and probabilistic behaviors to inform decisions that enhance system reliability and performance.

Ahmadi, R. (2020). A pioneering approach to optimizing maintenance for repairable parallel systems facing hidden failures presents a proactive strategy aimed at mitigating risks and enhancing system reliability. Hidden failures, which remain undetected until they cause system malfunctions, pose significant challenges in traditional maintenance planning due to their elusive nature. This innovative approach integrates advanced techniques such as condition monitoring, predictive analytics, and reliability-centered maintenance (RCM) principles.

ISSN PRINT 2319 1775 Online 2320 7876

 UGC CARE Listed (Group -I) Journal Volume 11, Iss 13, 2022

Condition monitoring systems continuously track system parameters and performance indicators, enabling early detection of anomalies that may signify hidden failures. Leveraging predictive analytics allows engineers to analyze historical data and trends to anticipate potential failure modes, prioritizing maintenance actions accordingly. Additionally, applying reliability-centered maintenance principles helps identify critical components prone to hidden failures, enabling the development of tailored maintenance strategies. By assessing the consequences of component failures and optimizing maintenance tasks, organizations can maximize system reliability while minimizing costs. Moreover, probabilistic models like Bayesian networks or Markov processes facilitate the simulation of different maintenance scenarios, enabling effective evaluation and optimization of maintenance schedules based on risk assessments and cost-benefit analyses. This proactive approach ensures that maintenance efforts are targeted where they are most needed, enhancing operational efficiency and extending the system's lifespan in a cost-effective manner.

Ahmadi, R et al (2018) Reliability modeling and maintenance optimization for repairable systems with heterogeneous populations demand a nuanced approach to address the diverse characteristics and behaviors of system components, ensuring optimal performance and longevity. The presence of heterogeneity introduces complexities that traditional homogeneous models may not adequately capture. Therefore, probabilistic models accommodating heterogeneity, such as mixture models or non-homogeneous Poisson processes, are essential. These models allow for the representation of various subgroups within the component population, enabling the estimation of their distinct failure and repair characteristics. Maintenance optimization strategies must be tailored to account for the varying reliability profiles of different component types. This entails prioritizing maintenance actions based on criticality, optimizing the frequency and type of tasks to address specific failure modes, and efficiently allocating resources. Predictive maintenance techniques, including condition-based monitoring and prognostics, play a crucial role by anticipating potential failures and prioritizing interventions based on individual component conditions. By leveraging real-time data and predictive analytics, organizations can time maintenance activities effectively, minimizing unplanned downtime and optimizing resource utilization. In essence, a comprehensive understanding of heterogeneous populations in both reliability modeling and maintenance optimization allows organizations to develop proactive strategies that enhance system reliability, minimize downtime, and optimize maintenance costs effectively.

ISSN PRINT 2319 1775 Online 2320 7876

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Srinivasa Rao, M et al (2014) Reliability analysis of repairable systems through system dynamics modeling and simulation offers a dynamic and comprehensive approach to understanding system behavior, identifying vulnerabilities, and optimizing maintenance strategies. System dynamics modeling involves representing the system as a network of interconnected components, where failures, repairs, and other events influence the system's behavior over time. In this context, repairable systems are modeled as dynamic entities with feedback loops, where failures trigger repair actions that impact the system's performance and reliability. By capturing the interactions between various system components, such as failure propagation, repair delays, and maintenance policies, system dynamics models can simulate the system's behavior under different operating conditions and maintenance scenarios. Simulation techniques allow analysts to evaluate the effectiveness of different maintenance strategies and policies in improving system reliability and minimizing downtime. Through scenario analysis and sensitivity testing, analysts can assess the impact of factors like repair times, component degradation rates, and maintenance intervals on system performance. Furthermore, system dynamics modeling facilitates the exploration of complex interactions and dependencies within the repairable system, including feedback loops, nonlinearities, and emergent behaviors. This holistic understanding enables engineers to identify critical points of failure, optimize maintenance schedules, and implement preventive measures to enhance system reliability. Moreover, system dynamics models can be continuously updated and refined based on real-world data and feedback, allowing for ongoing improvement and adaptation of maintenance strategies to evolving operational conditions and performance requirements.

Goyal, N et al (2019) Mathematical modeling of embedded systems under network failures is essential for understanding and addressing the challenges posed by communication disruptions. Embedded systems, which integrate hardware and software components to perform specific functions within larger systems or devices, often rely on network connectivity for data exchange and coordination. However, network failures such as packet loss, latency, or link failures can disrupt communication, leading to system malfunctions or degraded performance. In mathematical modeling, various approaches can be employed to represent the behavior of embedded systems under network failures. Probabilistic models, such as Markov chains or queuing theory, capture the stochastic nature of network disruptions and their effects on system operation, quantifying the probability of different failure scenarios and their impact on performance metrics. System dynamics modeling simulates how network failures propagate

ISSN PRINT 2319 1775 Online 2320 7876
 UGC CARE Listed (Group -I) Journal Volume 11, Iss 13, 2022

through the system and affect overall performance by representing interactions between system components. Additionally, fault-tolerant techniques like redundancy and error correction codes can be integrated into models to mitigate the impact of network failures on system reliability. Overall, mathematical modeling of embedded systems under network failures provides insights into system vulnerabilities, aids in optimizing communication protocols, and facilitates the design of robust, resilient systems capable of maintaining performance in challenging network environments.

Chemweno, P et al (2018) A review of dependability modeling approaches in maintenance decision-making sheds light on diverse methodologies employed to assess and manage risks effectively. Dependability modeling encompasses techniques aimed at quantifying system reliability, availability, maintainability, and safety, offering structured frameworks for analyzing system components' interplay and potential failure scenarios. One prevalent approach is fault tree analysis (FTA), systematically evaluating combinations of component failures leading to system-level failures, thereby prioritizing maintenance actions. Reliability block diagrams (RBDs) depict systems as interconnected blocks, aiding in reliability assessment and critical component identification. Markov models offer a probabilistic approach, analyzing system dynamics and informing maintenance policies over time. Dynamic fault tree analysis (DFTA) extends traditional fault tree analysis by incorporating time-dependent factors and dynamic system behaviors, enabling adaptive maintenance strategies in evolving environments. Through these methodologies, organizations can proactively identify and mitigate risks, optimize maintenance practices, and enhance system dependability and resilience effectively.

Aghili, S. J., et al (2017) Reliability evaluation of repairable systems using various fuzzy-based methods offers a powerful means to address uncertainties inherent in real-world data and expert judgments. Fuzzy logic, a mathematical framework that accommodates imprecision and uncertainty, provides several methodologies for modeling and analyzing system reliability. Fuzzy fault tree analysis (FFTA) extends traditional fault tree analysis by incorporating fuzzy logic to represent uncertainties associated with component failures and probabilities, enabling assessments under incomplete information. Similarly, fuzzy reliability block diagrams (FRBDs) model reliability relationships between system components, considering imprecise information about component reliability and interactions for a more realistic reliability assessment. Fuzzy Markov models integrate fuzzy logic to represent uncertain transition probabilities between system states, capturing vagueness in system behavior and facilitating

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reliability and availability evaluation over time. Moreover, fuzzy expert systems utilize fuzzy logic to aggregate expert knowledge and subjective judgments, providing insights into system reliability under various conditions. Overall, fuzzy-based methods offer a flexible and robust approach to handling uncertainties in repairable systems, aiding in the identification of critical failure modes and the optimization of maintenance strategies effectively.

Significance of the study

Exploring the performance of repairable systems through various mathematical models holds significant theoretical and practical implications. The research advances reliability engineering by deepening understanding of system dynamics, including factors affecting reliability, maintenance strategies, and failure patterns. Practically, insights gained benefit industries reliant on repairable systems, guiding decisions in maintenance planning, resource allocation, and system design. Optimal strategies identified can minimize downtime, reduce costs, and enhance productivity. the study facilitates the development of proactive maintenance techniques, improving system reliability by preemptively addressing potential failures. Additionally, research outcomes inform policy decisions, contributing to system reliability and safety standards. Ultimately, this research promises tangible improvements in system reliability, availability, and maintainability, fostering operational efficiency and service quality across diverse industries.

Research Problem

The research problem of exploring the performance of repairable systems via various mathematical models is multifaceted and central to ensuring the reliability and efficiency of complex systems. At its core lies the challenge of comprehensively understanding the intricate dynamics of repairable systems, including the interactions between failure events, maintenance actions, and overall system reliability over time. This necessitates the identification and application of suitable mathematical models capable of accurately capturing the stochastic nature of system behavior and the dependencies between system components. Additionally, the research problem involves assessing the practical utility of these models in real-world contexts, considering factors such as data availability, system complexity, and model assumptions. Furthermore, there is a need to investigate the effectiveness of different maintenance strategies, ranging from proactive approaches like preventive and condition-based maintenance to reactive measures such as corrective maintenance, in improving system performance. Optimizing resource allocation for maintenance activities within repairable systems is also a

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critical aspect of the research problem, requiring a careful balance between costs and benefits to maximize system reliability while minimizing operational expenses. Addressing these challenges through interdisciplinary research efforts can lead to significant advancements in enhancing the reliability, availability, and maintainability of repairable systems across diverse industries, ultimately contributing to improved operational efficiency and reduced downtime.

Conclusion

This review has provided an in-depth examination of various mathematical models used to analyze the performance of repairable systems. The Homogeneous Poisson Process (HPP) and Non-Homogeneous Poisson Process (NHPP) offer foundational insights into failure and repair patterns, though their limitations necessitate the use of more complex models like the Renewal Process. These models have demonstrated their utility in predicting system behavior and guiding maintenance strategies. Recent advancements in Bayesian approaches and machine learning techniques represent significant progress in this field, enabling more precise predictions and adaptive maintenance planning. These methods leverage prior knowledge and large datasets, enhancing the accuracy and applicability of performance assessments. However, challenges remain, particularly regarding data quality and the accurate estimation of model parameters, which can impact the reliability of predictions. The integration of emerging technologies and robust validation methods is crucial for further advancement. Future research should focus on developing hybrid models that combine traditional stochastic approaches with modern computational techniques to overcome existing limitations. Additionally, there is a need for more comprehensive validation studies to ensure the practical applicability of these models in diverse industrial contexts. the ongoing development of mathematical models for repairable systems is essential for optimizing maintenance strategies and improving system reliability. By selecting and applying the most suitable models, researchers and practitioners can better understand system dynamics, reduce downtime, and enhance operational efficiency. This review aims to serve as a guide in this endeavor, highlighting the strengths, limitations, and future directions of current modeling approaches.

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