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EXPLORING REDUNDANCY OPTIMIZATION TECHNIQUES FOR SYSTEM PERFORMANCE

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Abstract

System reliability optimization remains a dynamic and evolving challenge, influenced by continuous advancements in mathematical modeling, engineering innovation, and management strategies. This study includes documents on reliability, availability, maintainability, dependability, testability, cost-benefit analysis, life-cycle failures, maintenance modeling, and asset integrity management. However, this article is mainly concerned with documents that focus on redundancy optimization problems (i.e., k out of n system, warm, hot, cold standby redundancy, system reliability analysis in different failure and repair conditions, redundancy allocation in several system configurations, and so on) that apply to Telecommunications, Aerospace and Aviation, Industrial Automation, Network Servers and IT Systems, Transportation Systems. In addition, documents on the Oil and Gas Industry, Data Centers, and critical Infrastructure that are part of process industries are included. We analyze as many documents as possible by combining commonly used keywords. Additionally, the paper identifies emerging trends such as adaptive and hybrid redundancy strategies and the integration of intelligent techniques like Supplymentry variable techniques, regenerative point techniques, Genetic algorithm, and machine learning for real-time reliability management. By synthesizing findings from recent literature, this review aims to guide future research and practical implementations, supporting the design of cost-effective, robust, and resilient systems for modern computing environments.

Keywords: Reliability, Redundancy, Optimization, Operative unit, Redundant System, Activation time, Standby Units, Profit analysis, Regenerative Point Technique .

1. INTRODUCTION

Consumers' expectations for high functionality, high performance, and high dependability rise along with technology's advancements, which creates both obstacles and possibilities as modern engineered systems become more sophisticated. Despite extensive research and scrutiny, system reliability optimization problems continue to pose formidable challenges, as new complexities and difficulties emerge, perpetually impacting system reliability. The challenge of downtime can be addressed by the introduction of redundancy.

The reliability of redundant systems, as revealed through probabilistic analysis, hinges on three pivotal factors. Foremost among these is the failure rates or, equivalently, the lifetime distributions of the constituent components that comprise the system. Another crucial factor influencing system reliability is the system configuration, which encompasses both the number of components and their interconnectivity - in other words, how these components are arranged

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and linked to form the overall system. Lastly, system reliability is also contingent upon the maintenance strategies employed, including repair, corrective, and preventive measures, which collectively impact the system's overall performance and reliability.

Figure 1 depicts a conceptual framework for the current investigation's methodology.

Abbreviations used:

CSS   Cold Standby System
WSS   Warm Standby System
HSS   Hot Standby System
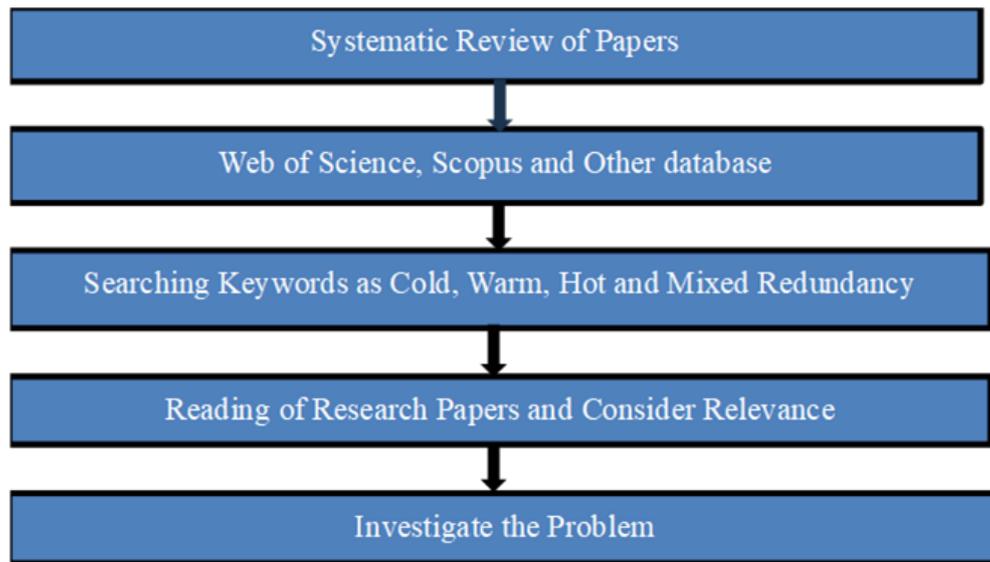RAP   Redundancy Allocation Problem

Figure 1: *Techniques for Systematic Analysis*

Because review papers can provide a concise and up-to-date overview of an area, they are essential to the scientific community. Numerous reviews in various areas of process reliability have been published. Dekker [27] gave an overview of the application of maintenance optimization models. Kuo and Parsad [55] demonstrated an overview of the methods developed for solving various reliability optimization problems. Kuo and Wan [56] looked at the best dependability design by primarily considering series-parallel systems, bridge networks, n-version programming architecture, k-out-of-n: G systems, and other unnamed coherent systems are among the systems. Yingkui and Jing [131] review the latest studies and advances in multi-state system reliability evaluation, optimization, and maintenance summarized. Li and Ding [60] briefly reviewed the allocation of active redundancies to systems. Ram [91] surveyed reliability approaches in various engineering fields and provided the major areas, i.e., past, current, and future trends of reliability methods and applications. Alaswad and Xiang [1] review the recent condition-based maintenance literature that emphasizes mathematical modeling and optimization approaches and focuses on the optimal design of CBM policies, including inspection frequency, inspection/maintenance quality, and optimization criteria. Amin et al. [4] Conducted a comprehensive bibliometric analysis of research on process system failure and reliability, providing insights into the development and trends of failure and reliability engineering within process systems.

This comprehensive study encompasses a broad range of topics, including reliability, availability, dependability, maintainability, testability, life-cycle failure assessment, cost-benefit analysis, maintenance modeling, and asset integrity management. However, the primary focus of this article lies in examining documents that specifically address redundancy optimization problems (i.e., k out of n system, warm, hot, cold standby redundancy, system reliability analysis in different failure and repair conditions, redundancy allocation in several system configurations, and so

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on) that apply to Telecommunications, Aerospace and Aviation, Industrial Automation, Network Servers and IT Systems, Transportation Systems. We analyzed as many documents as possible by combining frequently used keywords. However, certain documents may be overlooked without intention. We apologize to readers and scholars if we overlooked any pertinent documents.

2. Standby Redundancy

The redundant series system has been extensively studied due to its wide range of applications in practical systems such as power supply networks, photovoltaic energy systems, air traffic control equipment, and automated manufacturing lines. By integrating redundancy strategies with maintenance through component repairs, the reliability and efficiency of repairable systems can be significantly improved. In a standby system, operational units function while backup units remain inactive until needed. When an active unit fails, a standby unit is engaged to take its place. There are three main types of standby configurations: hot, warm, and cold standby as shown in Figure 2. The hot standby method ensures that both active and backup units operate in a similar environment, with the standby unit continuously connected to the system. This approach is particularly beneficial for applications requiring instant switchover, such as network printers and aircraft engines. Conversely, in the cold standby approach, the backup unit remains unpowered until the primary unit fails and requires replacement. This strategy is advantageous for systems prioritizing energy efficiency, such as those in metallurgy and defense applications. The warm standby approach serves as a middle ground between hot and cold standby. Here, the backup unit experiences a failure rate that falls between the two extremes. This method provides a balance between rapid switchover and energy conservation, making it a flexible and practical choice for various systems.
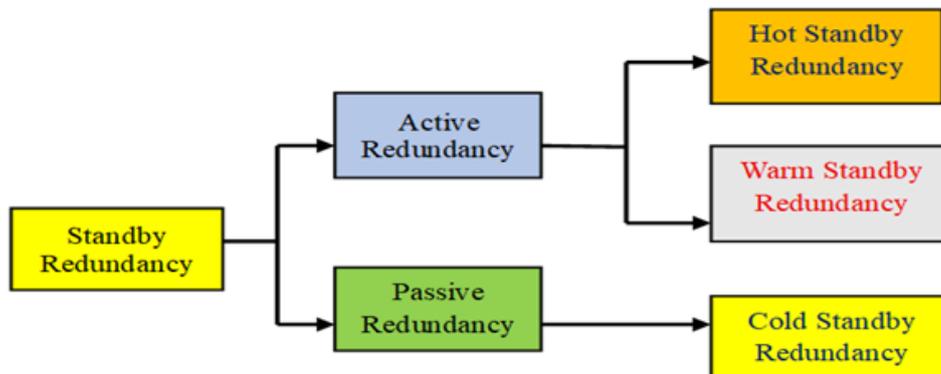

Figure 2: *Classification of Standby Redundancy*

3. Cold Standby Redundant systems

Cold standby redundancy is a configuration technique employed to boost the reliability and availability of essential systems by utilizing redundant components that remain inactive until needed. In this setup, the system consists of redundant components that are kept in a non-operational (standby) state until needed. The primary (active) component operates and performs its function, while the redundant components remain ready to take over if the operative unit fails. CSS are commonly used in critical applications where continuous operation is vital, such as in power distribution, telecommunications, aerospace, and transportation industries. Redundancy ensures that the system can continue to function despite failures, making it an effective approach to enhance the reliability and availability of the system. However, it also comes with additional redundant components and maintenance costs. Therefore, designing and optimizing a

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cold standby redundant system involves carefully balancing the benefits of improved reliability against the associated costs. Optimization of a CSS involves finding the best configuration and activation policy to maximize system reliability and availability while minimizing costs and resource utilization. The goal is to balance redundancy, which enhances system reliability, and the associated costs of maintaining redundant components.

Taneja et al. [112] discussed a single server two-unit CSS, where each unit can be in one of four modes: partial, normal, failure, complete failure, and partial failure with some repair already done, and priority is given to repairing the failed unit. Goel and Tyagi [36] described a two-unit priority redundant system with three modes: partial, normal and total failure, one unit has a priority in operation, while the other has a priority in repair. Tuteja and Taneja [116] analyzed a one-unit system with a single server with partial failure, which is subject to random inspection. Partial failures can only be identified through deliberate inspection, whereas complete failures are immediately detectable without the need for inspection. Bhat and Gururajan [15] considered one repair facility that supports a two-unit CSS by assuming that after a breakdown, the system continues to function for an arbitrary period.

Vanderperre [118] presented a cold standby redundant system that includes numerous switch-over devices and a monitor using arbitrary distribution and compared the performance of both systems while considering the scenario of a single switch-over device. Singh [102] investigated a two-unit CSS in which operation is affected by weather conditions.

Mahmoud et al. [65] Investigated a CSS comprising two units, incorporating complex maintenance policies such as periodic inspections, rest periods, replacements, setup times, and dual repair modalities. An expert repairman and his assistant were used in the analysis of a two-unit CSS by Kumar et al. [52] [53] . If the second unit fails while an experienced repairer is engaged in fixing the first, his assistant fixes it. Gopalan and Kumar [38] analyzed an n-unit CSS with a single repair facility using clustering and cutting the state space approximation methods with arbitrary distribution. Various state probabilities corresponding to different initial conditions are obtained using semi-regenerative phenomena.

Mokaddis et al. [73] deal with a two dissimilar unit CSS with random units working in two different modes. Smith [104] considers a 1 out of n repairable system with cold standby. Failed units can be replaced by spare units to reduce system downtime, followed by an approximation method and general failure and repair time distribution. Sridharan and Mohanavadivu [106] examined the behaviour of a 2-unit CSS with two different types of repairmen with the awareness that repairmen might not be able to complete a different repair within a reasonable amount of patience time. Zhang [136] examined a repairable CSS consisting of two identical components parts and a single repairman and found the best replacement policy to solve the problem requires maximizing the long-run expected benefit per unit of time. Chandrasekhar and Natarajan [23] investigated a repairable n-unit system operating in a random environment. The system's performance is governed by a Markov process, which determines the required number of units for satisfactory operation. Coit and Liu [25] proposed a methodology for solving the RAP in a series system composed of multiple k-out-of-n subsystems, aiming to identify the optimal solution. This issue had not yet been satisfactorily resolved, and the suggested approach provides the capacity to address a wider variety of engineering design issues. Rizwan et al. [94] [95] analyzed a two-unit CSS, which can operate in four possible modes with the assumption that whenever the operative unit fails, partially or directly, it goes under repair, and the standby unit is switched off immediately, and the repair facility, where the repairman tired after some random time and then his assistant did the remaining repair of the failed unit.

Wang and Loman [126] studied the general electric company suggested and developed an on-site power plant with N active generators and backup generator(s) in standby to create an incredibly reliable power source, where $k < N$ generators may supply enough power. Khaled and Mohamed [29] discussed a two-unit CSS with a single repair facility, the operative and standby units are switched out at random intervals with preventive maintenance. Vanderperre [119] provided an overview of the reliability of a renewable system with comprising cold standby units serviced by a single repairman. The specific scenario of deterministic failures yields an explicit

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exact result for the survival function of the duplex system.

Papageorgiou and Kokolakis [80] studied a $(2, n-2)$ parallel CSS where two units begin to operate simultaneously, and any one of them is instantly replaced by one of the $(n-2)$ warm standby on failure. They presumptively have n different, irreparable units available. Yu et al. [132] examined a CSS consisting of two similar components. Through probability analysis, they defined the system's cost rate as the optimization objective and treated the system's availability as a constraint. Zhang and Wang [137] investigated a cold standby repairable system with two different components with exponential distribution, and one unit is given priority in use. Some reliability indices are derived using geometric processes and supplementary variable techniques. Tavakkoli-Moghaddam et al. [114] developed a genetic algorithm-based framework to optimize redundancy allocation in series-parallel systems, by combining active and cold-standby redundancy strategies at the subsystem level. Azaron et al. [10] applied a genetic algorithm to optimize the reliability of a CSS consisting of k dissimilar, non-repairable units, addressing multiple conflicting objectives.

Bhatti et al. [17] examined a single repairman and two identical units of CSS using the concept of inspection policy for detecting the kind of failures (major and minor) before the failed unit gets repaired. Moghaddass et al. [72] explored the trade-off between optimal design and maintenance strategies for a repairable multi-state system composed of binary-state components. Chambari et al. [21, 22] developed a bi-objective model for the RAP in series-parallel systems, allowing both active and cold-standby redundancy techniques and further examined reliability allocation in non-repairable systems, applying a simulated annealing algorithm to solve large-scale problems efficiently. Levitin et al. [57] examined the 1-out-of-N: G heterogeneous CSS optimal standby component sequencing issue. Montoro-Cazorla and Perez Ocon [75] considered a system with n components, one online unit, and multiple cold standby units, with failed units being repairable. The Markov process that governs the system is built and analyzed in a transient and stationary domain, and the availability, reliability & failure rate are all computed. Manocha and Taneja [110] proposed a stochastic modeling approach for a 2-unit CSS, accounting for uncertain failure times and a two-phase repair strategy.

Malhotra and Taneja [68] assessed the performance of single-unit and two-unit CSS in a cable manufacturing plant, examining their reliability and efficiency under varying demand conditions, while Taneja et al. [111] extended this analysis by incorporating scheduled maintenance into the single-unit system and allowing both units in the cold standby to operate based on demand. Gupta [39, 40] analyzed single-unit and CSS, examining the effects of two different repairman types and resume/repeat policies, and further compared reliability models for CSS with one or two units, incorporating two types of repairmen and three distinct repair procedures. Batra and Taneja [11] developed four models for a system with two operational units and no/one/two and three standby units, respectively. By comparing the models, the number of standby units is optimized. Sharifi and Taghipour [100] explored the optimal inspection scheduling for a k-out-of-n system with non-identical components, utilizing a matrix-based method to determine system state transition probabilities and minimize expected total cost, while ensuring reliability.

Behboudi et al. [14] developed an innovative switching policy for two-unit CSS based on virtual age, showing that this approach significantly improves unit performance and system reliability in scenarios with increasing failure rates. Manocha et al. [70] examined a two non-identical unit CSS; the standby unit can be randomly checked to see if it is worth using or not, and a sensitivity analysis about MTSF and availability has also been performed. Wang et al. [120] developed effective approximation techniques, utilizing the central limit theorem, for reliability evaluation of k-out-of-n CSS, accommodating position-dependent component lifespan distributions. Chaudhary et al. [24] investigated a dual-unit system with one operational unit and one cold standby unit, assuming both units are identical. If any units fail after the first repair, they are replaced with a new unit with a single repairman facility. Raghuvanshi et al. [90] presented a cost-benefit analysis for a redundant system with two identical units in cold standby, accounting for minor and major failures, and continuous availability of two repair personnel. Lin et al. [59] discussed a hybrid subset simulation method paired with limit state equations for series-parallel

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CSS. Kumar and Sharma [51] relate the reliability measures analysis of two identical unit systems with a reboot facility. They assume that during unsafe failure, repair activity cannot be done immediately but first rebooting is done to transform unsafe failure into safe failure, and then repair activity is performed as usual.

4. Warm Standby Redundant systems

In warm standby systems, the redundant components are partially powered and in a pre-operational state, ready to take over the operation if the primary component fails. In contrast to CSS, which feature completely inactive backup components, warm standby components are partially powered and functional. The standby components in warm standby systems can be activated more quickly than those in. As a result, the switchover time from the operative unit to the standby unit is significantly reduced, thereby reducing downtime and improving overall system reliability. Rapid availability of standby components ensures that the system can quickly recover from failures, minimizing the impact on system operation. Warm standby systems offer a cost-effective compromise between cold standby and hot standby systems. Although they are more expensive to operate than CSS due to the partial power consumption, they are generally more cost-effective than hot standby systems. This type of redundant system is often employed in critical applications where downtime must be minimized. Industries such as telecommunications, data centers, and emergency response systems commonly use warm standby configurations. Alidrisi and Mustafa [2] presented a recursive approach to compute the reliability of a dynamic WSS consisting of n components, accounting for imperfect switching mechanisms and constant failure rates, and confirmed its accuracy through verification with established special cases.

Goel and Shrivastava [35] analyzed a 2-unit WSS assuming a bivariate exponential density and investigated the system's stochastic behavior and reliability characteristics. Mahmoud and Esmail [66, 67] analyzed the reliability of a two-unit WSS, considering failures due to both hardware malfunctions and human errors and further investigated the impact of a slow switch susceptible to these failures in such systems. Mokaddis et al. [74] investigated the reliability analysis of a two-unit WSS consisting of a priority unit and an ordinary unit, where a priority unit passes through different operative stages before it fails. Sridharan and Mohanavadivu [105] presented a cost analysis for a non-repairable standby system consisting of (n+m) identical units, evaluating the economic implications of the system. n units are needed for the system to function, while the remaining m units are warm standbys. Tuteja et al. [117] analyzed a 2-unit WSS with repairman waiting time, considering a dual-failure mechanism where units can transition to complete failure either directly or via an intermediate partial failure state. Arulmozhi [9] analyzed the system reliability of an M-out-of-N WSS with R repairmen to replace the failed components, and a closed-form equation was created. Additionally, the results of hot and CSS without repairmen are derived as special cases. Wang et al. [123, 125] conducted reliability and sensitivity analyses of complex repairable systems. In the first study, they examined a system with *M* operating machines, *S* warm standbys, and a repairable service station, analyzing the K-out-of-(M+S) system for different values of *K* and deriving expressions for system reliability and mean time to first failure (MTFF). In the second study, they investigated a repairable system with imperfect coverage, focusing on the impact of service pressure, where repairmen facing large queues could increase the repair rate to reduce the queue length.

Wang and Chiu [122] presented a steady-state availability analysis for three WSS models, accounting for imperfect fault coverage. The results are compared numerically, considering the impact of parameter values and the cost trade-offs between active and standby units. Perez Ocon and Montoro Cazorla [88] investigated warm standby n-unit systems with one operational unit and a single repairman facility, calculating availability, failure occurrence rates, and other relevant metrics. Srinivasan and Subramanian [107] developed a comprehensive model of a WSS consisting of three units and a single repair facility, to evaluate system reliability and performance. and by identifying certain regenerative points they have obtained, in principle, the reliability and availability function. Wang and Chen [121] compared the availability of three systems for

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three repair time distributions: exponential, gamma, and uniform with reboot delay and standby switching failures using the supplementary variable technique. Papageorgiou and Kokolakis [81] studied a $(2, n-2)$ parallel WSS where two units begin operating simultaneously, and any one of them is instantly replaced by one of the $(n-2)$ warm standby upon failure. They presumptively have n different, irreparable units available.

Eryilmaz [30] investigated the number of surviving warm standby components in a coherent system at the point of failure. The expected number of active warm standby components was utilized to establish the optimal initial allocation of standby components, aiming to minimize the expected total cost. Zhai et al. [135] introduced a novel binary decision diagram-based methodology for evaluating the reliability of k-out-of-(n+k) WSS, incorporating fault level coverage and enabling efficient analysis of complex system configurations. Aote et al. [5] presented the concept of particle S warm optimization, and work carried out on PSO by different researchers. Wells [127] examined an n-unit system with a single warm standby. Individual components may fail repair, but the entire system may break irreparably at some finite but random period in the future.

Ruiz-Castro [96] discussed a complex K-unit system, where one unit is online while the others are on warm standby, facing various types of failures. Utilized a discrete-time marked Markovian arrival process (DMAP) to represent and analyze preventive maintenance activities with an indefinite number of repair personnel. Delia and Rafael [76] considered a system with n components, one online and the rest on warm standby subject to repair, and extended many other systems due to the generality of the Markovian arrival process. Jia et al. [44, 45, 46] explored various reliability aspects of two-unit standby systems, including an active repair-free switching policy, demand-based WSS accounting for component deterioration and start failure, and developed an analytical method using a multistate decision diagram to assess reliability considering the activation probabilities of standby units.

Bhatia et al. [16] examined a three-unit induced draft fan system installed in boilers used in thermal power plants through a probabilistic analysis. Three induced draft fans are installed in the boiler under consideration: two are operational, and one is warm standby redundancy. Finkelstein et al. [31] proved that for a 1-out-of-n WSS, the optimal component activation sequence corresponds to arranging components in ascending order of their expected lifetimes, thereby maximizing system efficiency. Hadipour et al. [42] Introduced a new mathematical framework to analyze and optimize systems utilizing repairable components, where the subsystem can use both active and warm standby strategies simultaneously by series-parallel elements. Liu et al. [62] considered a warm standby n-unit system under N-policy with one repairman taking multiple vacations. Here, the system is analyzed by two methods: first, a Markov process, and second, matrix-analytical approaches. Yen et al. [130] investigated and compared four retrial systems with warm standby units, imperfect coverage, and exponentially distributed repair times, evaluating their cost-effectiveness and benefits.

Yang and Wu [129] presented a Markovian analysis to evaluate the availability and reliability of a repairable system with warm standby components, considering switching failures and a single repair facility. Levitin et al. [58] contributed by modeling and optimizing the replacement and maintenance schedule (RMS) for a heterogeneous dual-unit WSS to reduce the total predicted mission cost, which includes operation, standby, and maintenance costs as well as mission failure penalty costs. Juybari [47] studied a 1-out-of-n: G repairable WSS using a mixed redundancy method under environmental shocks. Kumar and Kumar [54] analyzed the behaviour of the parallel model with one operative and one warm standby unit with two repairman facilities. Bhat and Simon [18] investigated a two-unit warm standby redundant system, considering the impact of varying repair facility efficiency, equivalently, repair capacity decreases upon each repair.

5. Hot Standby Redundant systems

In hot standby systems, the redundant components are continuously powered and fully operational, running in parallel with the primary component. Facilitates seamless switching to the

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standby component, minimizing downtime in the event of primary component failure. Hot standby systems feature near-instantaneous activation of the standby component, ensuring minimal downtime. As the standby component is already operational, the transition from primary to standby operation occurs immediately upon primary component failure, resulting in minimal to no downtime. The continuous operation of the redundant components ensures that the system can with stand component failures without any disruption in performance. Hot standby redundant systems are commonly used in mission-critical applications where uninterrupted operation is paramount. Examples include air traffic control systems, power distribution grids, and emergency response centers. This type of standby system consumes more resources, including power and maintenance efforts, due to the continuous operation of redundant components. This higher utilization of resources comes with increased operational costs. The Continuous operation of the standby components requires regular testing and maintenance to ensure their readiness. Taneja [113] presented and analyzed two reliability models for a HSS consisting of two identical units. In the second model, the failures of the units are immediately observed, whereas in the first model, a unit's failure is not self-revealed and is only identified when both units fail. Duhan et al. [28] presented a reliability analysis of a two-unit hot standby PLC system, considering corrective and preventive maintenance, and two repair scenarios, to evaluate system performance and reliability.

Tuteja et al. [115] dealt with a two-unit HSS where programmable logic controllers are used as hot-standby which fail with lower failure of the operative unit and three types of failure - minor, major (repairable), and major (irreparable). Parashar and Taneja [85] analyzed a system wherein two PLCs are working in a master-slave fashion. The master unit has the priority of operation and repair over the slave unit with three types of failure: minor, major-repairable, and major-irreparable. Rizwan et al. [93] offered a reliability analysis of a two-unit hot standby PLC system using data gathered from an industry where various failure types are documented and modeled. Singh et al. [103] Examined a database system consisting of a primary database and a hot standby database unit, which utilizes online archive redo log transfers for real-time replication. Manocha et al. [71] proposed a stochastic model characterized by discrete state space and continuous time to analyze a system comprising a primary unit and a hot standby database unit, considering multiple failure modes. Batra and Taneja [11] [13] developed three models for a system with one/two operational units and no/one/two hot standby units. The models are compared to determine the optimal number of hot standby units to utilize.

6. Mixed Standby Redundant systems

The term "mixed" implies that the redundant components or subsystems are not identical. They might have different designs, specifications, or functionalities. This approach can be cost-effective and allows for flexibility in choosing components based on specific requirements. The primary goal of mixed standby redundant systems is to enhance fault tolerance. By having diverse components as backups, the system can better withstand failures or faults in individual elements. Implementing mixed standby redundancy involves a balance between the cost of redundant components and the potential benefits in terms of increased reliability and fault tolerance. A cost-benefit analysis helps to determine the most suitable approach for a given application. Mixed standby redundant systems are commonly used in critical infrastructure, aerospace, industrial automation, telecommunications, and other sectors where reliability and continuous operation are paramount. Jacob et al. [43] examined the reliability evaluation of a repairable two-unit standby system with deterioration, considering the impacts of human error and common cause failure on system performance.

Wang and Kuo [124] deal with the availability and reliability characteristics of four different series system configurations with cold and warm standby components; also, MTTF availability for four configurations is obtained, and comparisons are made. Rao and Gupta [92] studied the M/G/1 machine repairable problem, which consists of K working machines and Y spare machines, which are classified as being either cold, warm, or hot standby, and a single repairman, is modeled and analyzed using supplementary variable techniques. Sarhan [98] determined

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the reliability equivalence factors of a series system consisting of n independent, non-identical components with exponential failure distributions. Chakravarthy et al. [20] investigated a k-out-of-n reliability system in which a single faulty server maintains n identical components. De Smidt-Destombes [26] investigated the relationship between repair capacity, spare part inventories, and preventive maintenance policies for a k-out-of-N system and analyzing its reliability and availability. Papageorgiou and Kokolakis [79] studied a (2,n-2) parallel system where two units begin operating simultaneously, and any one of them is instantly replaced by one of the (n-2) standbys upon failure. They presumptively have n different, irreparable units available. Gen and Yun [33] provided a brief overview of GA-based approaches for several reliability optimization problems, including bicriteria reliability optimization with fuzzy goals, and introduced hybrid approaches for combining GA with fuzzy logic.

Kokolakis and Papageorgiou [50] focused on the evaluation of system reliability using recursive relation and optimization of starting times for non-identical, non-repairable units with at most n units in parallel even through a single unit is sufficient and also provides analytical results for some special distribution and moderate value of n. Cha et al. [19] developed a comprehensive framework for modeling standby systems, including cold, hot, and warm standby scenarios, assuming exponential distributions for unit lifetimes, and deriving various system performance measures. Yun and Cha [134] considered a two units standby system, where the first unit begins operating and the second unit is initially in the cold standby state. If the operating unit fails, the second unit is switched from warm standby to active after a certain period called switching time has passed, and if the first unit fails before this time, the system fails.

Mahato et al. [64] addressed the reliability-redundancy optimization problem by treating the reliability of each component as an interval-valued number. This involves choosing components with various redundancy levels that maximize system reliability. Gupta and Gupta [41] examined a reliability model's profitability analysis for a single-unit system that includes inspection, replacement, repair, and preventive maintenance. Sharma and Kaur [101] analyzed the possibility of finding an operational compressor unit in a milk processing facility with various types of failures: serviceable, repairable, and replaceable. Malhotra and Taneja [69] analyzed the comparison of two stochastic models of a cable manufacturing plant subjected to inspection and scheduled maintenance with reinstallation/reconditioning failure and replacement failure. Ardakan et al. [7] discussed optimizing the RAP using a mixed redundancy strategy in a system to improve its reliability by offering greater flexibility to system designers.

Ke et al. [49] looked into a solution for fixing machines that had common failures with standby switching and average repair timeframes. Kayedpour et al. [48] discussed the RAP in repairable systems, developing a methodology to optimize system reliability and availability, considering the selection of configuration strategies such as parallel, warm, and cold standby subsystems. Gholinezhad and Hamadani [34] discussed the redundant allocation problem and proposed a new model that allows for component mixing, where different types of components can be used in each subsystem. The objective of the RAP is to optimize system reliability while satisfying key constraints, including budget limitations, weight restrictions, and spatial considerations.

Taj et al. [109] estimated various reliability indices by analyzing a 3-unit cable plant subsystem. Peiravi et al. [86, 87] addressed the RAP in reliability optimization by introducing the K-mixed redundancy strategy, which combines active and standby approaches. They developed a genetic algorithm to solve the problem and compared the results with previous studies' results. Additionally, they created a mathematical model based on a Markov approach to evaluate its effectiveness in a series-parallel system, again using a genetic algorithm and comparing the results with previous work. Taj et al. [108] compared the profit results of three reliability models for a building cable production facility. To estimate optimized reliability indices of the plant semi-Markov process and regenerative point techniques are used. Ruiz-Castro and Juan [97] investigated the reliability of a k-out-of-n system with n initial units, where units are susceptible to internal failures (repairable and non-repairable), external shocks, and random inspections, with arrivals modeled by a Markovian arrival process.

Golmohammadi and Ardakan [37] presented a reliability model for a system composed of

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active and standby units with the standby once proven to degradation by adopting periodic inspection and preventive maintenance policy. Ardakan et al. [6, 8] introduced a novel standby strategy structure that allows a component to begin operation at a predefined time without a switching system, while also optimizing the activation sequence of units in the subsystem by focusing on the genetic algorithm's encoding process, objective function, crossover, and mutation through various strategies, including active, standby, mixed, and K-mixed. Liu et al. [63] proposed a three-component repairable system under a K-mixed redundancy strategy with unreliable switching failure.

Parveen et al. [82, 83, 84] establish a reliability model considering one operative unit and N cold/warm /hot standby unit with the concept of activation and switching time and optimize the number of standby units for N=1,2 and 3. Saxena et al. [99] discussed a two non-identical unit parallel system to analyze the classical and Bayesian estimation of various measures of system effectiveness with a single repairable facility. Yadav et al. [128] examined a repairable system consisting of four non-identical units, employing the Markov approach to evaluate system reliability and availability. The reliability metrics for the system have been obtained by solving the Chapman-Kolmogorov equations using Laplace transformation techniques. Gao [32] discussed the analysis and optimization of repairable systems and different redundancy strategies, including mixed redundancy and K-mixed redundancy with dependent failures and variable repair rates, and provided the steady-state distribution, reliability analysis, and transient availability analysis of the system using Markov renewal theory. Alkaff [3] looked at broad standby systems with numerous primary and backup systems. Every single primary runs at a uniform warmness level of one. Every backup runs at a warmness level that can be adjusted: the levels go from (cold to hot standby) with intermediate values denoting warm standby. Li et al. [61] examined reliability analysis and phased mission systems optimization for backup/rescue operations and mixed redundancy strategies. Munda and Taneja [77] analyzed a system comprised of one operative unit, one cold and one warm standby unit and obtained various measures of system effectiveness. Qi et al. [89] proposed an innovative maintenance strategy for a two-component WSS, incorporating both cold and warm standby states to optimize system performance and availability. Oszczypala et al. [78] utilized a hybrid approach, combining genetic algorithms with continuous-time Markov chain modeling, to optimize redundancy allocation in series systems with k-out-of-n subsystems, focusing on maximizing system availability.

7. Conclusion

An attempt has been made to provide a brief overview of earlier works in each field and has included some of the most well-known publications in the literature for each classification so that interested readers can refer to them and locate additional relevant publications to thoroughly examine. The present research investigates and optimizes three types of redundancy optimization problems from different perspectives, including cold, warm, and hot standby redundancy in repairable and non-repairable systems.

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